UNIVERSIDAD DE CÓRDOBA

TESIS DOCTORAL

ANÁLISIS TECNO-ECONÓMICO PARA LA OPTIMIZACIÓN DE CENTRALES TERMOSOLARES DE CONCENTRACIÓN CILINDRO PARABÓLICA CON ALMACENAMIENTO TÉRMICO

TECHNO-ECONOMIC ASSESSMENT FOR THE OPTIMIZATION OF PARABOLIC TROUGH SOLAR THERMAL POWER PLANTS WITH THERMAL STORAGE

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UNIVERSIDAD DE CÓRDOBA
ESCUELA POLITÉCNICA SUPERIOR
COMPUTACIÓN AVANZADA, ENERGÍA Y PLASMA

CÓRDOBA, 2020

TITULO: *ANÁLISIS TECNO-ECONÓMICO PARA LA OPTIMIZACIÓN DE CENTRALES TERMOSOLARES DE CONCENTRACIÓN CILINDRO PARABÓLICA CON ALMACENAMIENTO TÉRMICO*

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TÍTULO DE LA TESIS: Análisis tecno-económico para la optimización de centrales termosolares de concentración cilindro parabólica con almacenamiento térmico.

DOCTORANDO: Jorge M. Llamas Aragonés

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El doctorando Jorge M. Llamas Aragonés ha realizado bajo nuestra dirección la tesis doctoral titulada "*Análisis tecno-económico para la optimización de centrales termosolares de concentración cilindro parabólica con almacenamiento térmico*".

Jorge M. Llamas Aragonés presentó sus primeros resultados en esta línea de investigación con "*Optimal models for concentrating solar power plants by storage and overflow systems" en el congreso internacional MIXGENERA, en Madrid (2011), donde inició sus trabajos en la simulación de operación con obsolescencia programada de una planta solar térmica de concentración con almacenamiento, mediante tecnología de colectores cilindro parabólicos.*

Jorge M. Llamas Aragonés ha realizado la mayor parte del trabajo de investigación de su tesis doctoral en colaboración con las empresas. Para ello, ha realizado diferentes visitas a un total de 10 plantas termosolares, tanto de Colectores Cilindro parabólicos como de Receptor Central, ubicadas en las provincias de Badajoz, Cáceres, Córdoba y Sevilla. La implementación de modelos y su calibración se ha realizado a través de los datos reales obtenidos de la Planta Termosolar "*La Africana*" de Córdoba. Para este proceso, la colaboración de D. Ramón Medio y D. Juan Manuel Vizcaíno, Director de la Planta y Responsable de Operaciones respectivamente, han sido fundamentales.

El avance en esta línea de trabajo propició la publicación "*World location as associated factor for optimal operation model of parabolic trough concentrating solar thermal power plants*" presentada en el congreso internacional *16th IEEE International Conference on Environment and Electrical Engineering,* en Florencia (2016).

Una vez concluida esta fase, Jorge M. Llamas Aragonés ha desarrollado la última etapa de la tesis consistente en la realización del análisis de los aspectos técnicos, parámetros económicos y estrategias de operación de plantas solares de concentración mediante colectores cilindro parabólicos. Este análisis ha permitido, partiendo de un modelo preciso de planta existente, parametrizar su diseño, dimensionado y modo operación.

Esta parametrización ha permitido la construcción de un modelo óptimo de planta acorde a cada instalación en particular, considerando como variables su ubicación geográfica, el dimensionado del campo solar, el sistema de almacenamiento térmico y su tamaño, las características del mercado eléctrico y la capacidad de producción eléctrica.

El trabajo de investigación de Jorge M. Llamas Aragonés ha requerido el desarrollo de modelado matemático y simulación. Los resultados de estos trabajos de investigación han dado lugar a distintas publicaciones entre las que cabe destacar: tres artículos publicados en revistas internacionales de impacto (Q2), así como distintas comunicaciones en dos congresos de carácter internacional y un congreso de carácter nacional.

Del doctorando, aparte de su excelente calidad humana, nos gustaría destacar, entre otras cualidades, su extraordinaria capacidad de trabajo, así como su constancia, tesón y disciplina, valores que han soportado todo el trabajo de investigación desarrollado y que han contribuido a resolver las numerosas dificultades inherentes al trabajo de investigación experimental desarrollado. Los Directores de esta tesis consideran que este periodo ha permitido que el doctorando desarrolle las cualidades propias de un excelente investigador.

Concluyendo, la metodología, calidad científica y resultados de investigación de esta tesis se valoran de forma MUY FAVORABLE.

Por todo ello, SE AUTORIZA LA PRESENTACIÓN DE LA TESIS DOCTORAL.

Córdoba, 24 de diciembre de 2019

Firma de los directores

Fdo.: Manuel Ruiz de Adana Santiago   Fdo.: David Bullejos Martín

ANÁLISIS TECNO-ECONÓMICO PARA LA OPTIMIZACIÓN DE CENTRALES TERMOSOLARES DE CONCENTRACIÓN CILINDRO PARABÓLICA CON ALMACENAMIENTO TÉRMICO

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A Carlos, Jorge y Ana,

Por vuestro apoyo, constancia, espíritu luchador y amor por las pequeñas cosas.

AGRADECIMIENTOS

A mis Directores de esta Tesis Doctoral. Al Profesor Doctor D. Manuel Ruiz de Adana, por su invalorable dirección y orientación durante el proceso de formulación y realización de este trabajo. Al Profesor Doctor D. David Bullejos, por su permanente apoyo, orientación, colaboración, consejo y crítica constructiva.

Al departamento de Ingeniería Eléctrica de la Escuela Politécnica Superior de Córdoba, cuyo profesorado me ha guiado y orientado en mi desarrollo profesional. En especial al Profesor Doctor D. Vicente Barranco López, con quien comencé mi andadura como doctorando en esta escuela.

A la Profesora Doctora Dña. Elena Gómez, por su colaboración en la revisión gramatical y orientación idiomática de las publicaciones que acompañan a este trabajo.

A las personas que de una forma u otra han sido claves en mi carrera profesional, colegas y compañeros, por confiar en mi juicio y criterio.

A mis familiares y amigos por su apoyo incondicional. Su confianza y ánimo me han ayudado a perseguir mis sueños, entre otros, a la realización de esta Tesis Doctoral.

A mis padres y hermanos. Sin ellos la vida tendría otro color.

A todos mi más profundo agradecimiento.

PREFACIO

La presente Tesis Doctoral tiene por título *Análisis tecno-económico para la optimización de centrales termosolares de concentración cilindro parabólica con almacenamiento térmico*. Ha sido elaborada por D. Jorge M. Llamas Aragonés, y forma parte de los requisitos para la obtención del Título de Doctor en Ingeniería Industrial. Se enmarca dentro del Programa de Tercer Ciclo "Computación avanzada, energía y plasma" incluido en la línea de investigación "Energía y tecnologías de la información".

La dirección de esta Tesis Doctoral ha sido realizada, como Director por el Profesor Doctor D. Manuel Ruiz de Adana Santiago, perteneciente al Departamento de Química, Física y Termodinámica Aplicada, área de Máquinas y Motores Térmicos, de la Universidad de Córdoba; como Codirector por el Profesor Doctor D. David Bullejos Martín, perteneciente al Departamento de Ingeniería Eléctrica.

Esta Tesis Doctoral supone la continuación de una línea de investigación iniciada en 2011, con el Profesor Doctor D. Vicente Barranco López del Departamento de Ingeniería Eléctrica de la EPS de Córdoba, referida la simulación de operación con obsolescencia programada, de una planta solar térmica de concentración con almacenamiento, mediante tecnología de colectores cilindro parabólicos.

Esta primera etapa permitió conocer de forma precisa los diferentes elementos que componen las plantas termosolares de concentración, así como su operación y adaptación a la demanda del mercado eléctrico. De igual modo, estableció la estructura y contenido de modelos matemáticos, para la simulación y predicción del comportamiento de los componentes termodinámicos, dentro de la tecnología de Colectores Cilindro parabólicos. Etapa en la que se realizan diferentes visitas a un total de 10 plantas termosolares, tanto de Colectores Cilindro parabólicos como de Receptor Central, ubicadas en las provincias de Badajoz, Cáceres, Córdoba y Sevilla.

Una vez realizada la implementación de modelos, se procede a su calibración a través de los datos reales obtenidos de la Planta Termosolar "La Africana" de Córdoba. Para este proceso, la colaboración de D. Ramón Medio y D. Juan Manuel Vizcaíno, Director de la Planta y Responsable de Operaciones respectivamente, han sido fundamentales.

La labor de investigación de esta Tesis Doctoral versa sobre el análisis de los aspectos técnicos, parámetros económicos y estrategias de operación de este tipo de plantas. Se centra, partiendo de un modelo preciso de planta existente, en parametrizar su diseño, dimensionado y modo operación.

El objetivo de esta parametrización es el modelado óptimo de planta acorde a cada instalación en particular, considerando como variables su ubicación geográfica, el dimensionado del campo solar, el sistema de almacenamiento térmico y su tamaño, las características del mercado eléctrico y la capacidad de producción eléctrica.

Finalmente, la supervisión y tutela de esta Tesis Doctoral por los Profesores Doctores D. Manuel Ruiz de Adana y D. David Bullejos, y sus contribuciones en el establecimiento de hipótesis, parametrización e implementación de modelos y análisis de los resultados, han sido vitales en la elaboración de este trabajo.

Esta Tesis Doctoral se presenta como compendio de seis artículos revisados por pares. Tres de los cuales (marcados en negrita) han sido publicados en revistas indexadas en la publicación *Journal Citation Reports* (JCR), cumpliendo así con los requisitos de las Directrices Reglamentarias para los Estudios de

Doctorado de la Universidad de Córdoba. Las tres publicaciones restantes corresponden a congresos nacionales e internacionales. La relación de artículos que componen este trabajo se muestra a continuación.

Artículo 1. Bullejos, D.; Llamas, J.; Carmona, F. Optimal models for concentrating solar power plants by storage and overflow systems. In Mixgenera 2011, options for the future, Madrid, Spain, 17 November 2011; UC3M: Madrid, Spain, 2011; 1-4.

Artículo 2. Llamas, J.; Bullejos, D.; Barranco, V.; de Adana, M.R. World location as associated factor for optimal operation model of Parabolic Trough Concentrating Solar Thermal Power Plants. In Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; IEEE: Florence, Italy, 2016; 1–6. DOI: 10.1109/EEEIC.2016.7555718.

Artículo 3. Llamas, J.; Bullejos, D; Barranco, V.; de Adana, M. R. Regulation issues for renewable energy integration into electrical markets. In Proceedings of the IEEE 17th International Conference on Environment and Electrical Engineering (EEEIC), Milan, Italy, 6-9 June 2017; IEEE: Milan, Italy, 2017; 1-6. DOI: 10.1109/EEEIC.2017.7977528.

Artículo 4. **Llamas, J.; Bullejos, D.; Ruiz de Adana, M. Techno-Economic Assessment of Heat Transfer Fluid Buffering for Thermal Energy Storage in the Solar Field of Parabolic Trough Solar Thermal Power Plants.** ***Energies*** **2017, 10(8), 1123. DOI: 10.3390/EN10081123.**

Artículo 5. **Llamas, J. M.; Bullejos, D.; Ruiz de Adana, M. Optimal Operation Strategies into Deregulated Markets for 50 MWe Parabolic Trough Solar Thermal Power Plants with Thermal Storage. *Energies* 2019, 12(5), 935. DOI: 10.3390/EN12050935.**

Artículo 6. **Llamas, J. M.; Bullejos, D.; Ruiz de Adana, M. Optimization of 100 MWe Parabolic-Trough Solar-Thermal Power Plants Under Regulated and Deregulated Electricity Market Conditions. *Energies* 2019, 12(20), 3973. DOI: 10.3390/EN12050935.**

RESUMEN

Dentro de la tecnología de receptor central, el campo de colectores cilindro parabólicos es el sistema de generación de electricidad por fuente renovable de mayor implantación a nivel mundial. Además, los avances en diseño y fabricación permiten definir parámetros específicos adaptados a la localización de la planta, requerimientos técnicos y tipo de mercado eléctrico. Avances que proporcionan una importante reducción de los costes de implantación.

Partiendo de la elaboración del marco teórico y del establecimiento de un modelo matemático para una central real en operación de $50MW_e$ con almacenamiento térmico mediante doble tanque de sales fundidas, el método de optimización presentado establece propuestas que permiten conocer las proporciones óptimas de dimensionado del campo solar, tipo y sistema de almacenamiento térmico y modo de operación de la planta de generación.

Esta Tesis Doctoral tiene como finalidad establecer estrategias encaminadas a maximizar la viabilidad y rendimiento tecno-económico de este tipo de centrales de generación eléctrica. Por tanto, el dimensionado y operación óptimos de planta se presenta como objetivo principal de este trabajo, considerando como variables de decisión, el lugar de implantación, dimensionado del campo solar, almacenamiento de energía térmica y tipo de mercado eléctrico.

Los resultados obtenidos se agrupan en seis bloques, dimensionamiento óptimo del campo solar, optimización del sistema de almacenamiento térmico, reducción de los costes de implantación, optimizar la producción de electricidad, y aumentar los beneficios de la venta de energía eléctrica. Se ha desarrollado un sistema de almacenamiento térmico innovador a través de la

generación de un bucle de fluido térmico dentro del campo solar denominado *"HTF Buffering"*. Los valores del coste nivelado de electricidad y del factor de capacidad obtenidos del entorno de simulación, posicionan a *"HTF Buffering"* como una alternativa tecno-económica viable a los sistemas tradicionales de almacenamiento de energía térmica para este tipo de centrales de generación. Así mismo, La optimización de operación de una planta de 50 MW_e con almacenamiento térmico mediante doble tanque de sales fundidas, dentro de mercado eléctrico no regulado, ofrece un aumento respecto a los sistemas de generación estándar, tanto de producción como de beneficio de venta de electricidad. Por su parte, el estudio de una central de 100 MW_e con almacenamiento por doble tanque de sales fundidas, considerando mercados regulado y no regulado, ofrece el tamaño de planta y operación de mercado óptimos acorde a cada una de los escenarios de radiación solar estudiados.

Así, los resultados presentados en este trabajo aportan respuestas a factores clave para los estudios de viabilidad, procesos de implantación y modo operación de plantas termosolares con tecnología de colectores cilindro parabólicos, son aplicables independientemente del tamaño de la planta de generación, y posibilitan la optimización de costes en los procesos de implantación y operación.

ABSTRACT

Within solar reception technology, parabolic trough is the most implemented renewable energy system for electric energy generation worldwide. Moreover, progress in design and manufacturing let defining specific parameters adapted to the plant location, technical requirements and the electricity market type. Advances that provide an important investment costs reduction.

Thus, starting from the state of the art and the implementation of a mathematical model for a real parabolic trough solar thermal power plant of $50MW_e$ with thermal storage, the optimization method presented attempts to establish strategies aimed at maximizing the plant investment viability and techno-economic performance.

This Doctoral Thesis focus on the establishment of strategies aimed at maximizing the feasibility and technoeconomic performance of this type of power plants. Thus, optimal plant sizing and operation is presented as the main objective of this work, considering as decision variables, the implementation area, sizing of the solar field, storage of thermal energy and type of electric market.

The results obtained are grouped into six blocks, optimal sizing of the solar field, optimization of the thermal storage system, reduction of implementation costs, greater electricity production, and increase the profits of the sale of Electricity.An unpublished thermal storage system has been developed throughout the generation of a thermal fluid loop within the solar field called "HTF Buffering". The values of the levelized cost of electricity and the capacity factor, obtained from the simulation environment, position "HTF Buffering" as a

viable techno-economic alternative to traditional thermal energy storage systems for this type of power plants. Likewise, the optimization of the operation of a 50 MW_e plant with thermal storage by double tank of molten salt, within unregulated electrical market, offers an increase over standard generation systems in both production and profit from electricity sales. Besides, the study of a 100 MW_e plant with storage by double tank of molten salts, considering regulated and unregulated markets, offers the optimization of the plant size as well as the optimal market operation according to each of the solar radiation scenarios studied.

The conclusions herein presented provide answers to key factors for feasibility studies, implementation processes, plant managing and operation of parabolic trough solar thermal power plants. They are applicable regardless the size of the power plant as well as enable cost optimization in the implementation and operation processes.

ÍNDICE DE FIGURAS

NOMENCLATURA

CCP	COLECTORES CILINDRO PARABÓLICOS
CSP	CONCENTRATING SOLAR POWER
DEM	DEREGULATED ELECTRICITY MARKET
DNI	DIRECT NORMAL IRRADIANCE (kWh/m^2)
HCE	HEAT COLLECTOR ELEMENT
HTF	HEAT TRANSFER FLUID
LCOE	LEVELIZED COST OF ELECTRICITY (k€/GWh$_e$)
MIBEL	MERCADO IBÉRICO DE ELECTRICIDAD
NWE	NORTHWEST EUROPE
OMEL	OPERADOR DEL MERCADO ELÉCTRICO
OMIE	OPERADOR DEL MERCADO IBÉRICO DE ENERGÍA
PCR	PRICE COUPLING OF REGIONS
PHO	PROGRAMA HORARIO OPERATIVO
PSA	PLATAFORMA SOLAR DE ALMERÍA
PT	PARABOLIC TROUGH
REE	RED ELÉCTRICA ESPAÑOLA
REM	REGULATED ELECTRICITY MARKET
RTE	RÉSEAU DE TRANSPORT D'ÉLECTRICITÉ
SEGS	SOLAR ELECTRIC GENERATION SYSTEM
SWE	SOUTHWEST EUROPE
SM	SOLAR MULTIPLE
TES	THERMAL ENERGY STORAGE

INTRODUCCIÓN

… el principio es lo más importante en toda obra,…
PLATÓN
LA REPÚBLICA. LIBRO II, XVII

GENERACIÓN ELÉCTRICA MEDIANTE PLANTAS DE CONCENTRACIÓN SOLAR CON TECNOLOGÍA DE COLECTORES CILINDRO PARABÓLICOS

El sistema de captación mediante colectores cilindro parabólicos (CCP) orientado a la producción de electricidad se encuadran en plantas termosolares *"Solar Electric Generating System"* (SEGS) [*Odeh et al., 2003*]. Este sistema está formado por espejos cilíndricos cuya sección transversal es una parábola, de tal forma que la radiación solar se concentra en el eje central focal en la que se sitúa el receptor (tubo absorbedor). Este sistema dispone de seguidores solares de concentración sobre tubos de alta eficiencia térmica que transportan aceite sintético, vapor de agua o sales fundidas, como elemento de transmisión térmica *"Heat Transfer Fluid"* (HTF). Su temperatura nominal de trabajo fluctúa entre 380 y 550°C en función de las características del fluido caloportador, y son susceptibles de acoplamiento con sistemas de almacenamiento térmico mediante intercambiador [*CIEMAT, 2009*], [*IEA, 2010*]. Dentro de esta tecnología, en 1997 se implanta en la provincia de Almería (España) una planta de ensayos pionera a nivel mundial con este tipo de tecnología, la Plataforma Solar de Almería (PSA) [*Lüpfert et al, 2001*].

En generación de energía eléctrica con almacenamiento térmico, la tecnología de receptor central tipo CCP es la de mayor extensión en su uso, por sencillez técnica y viabilidad económica [*Richter et al., 2009*].

La tecnología HTF consiste en utilizar un medio de transferencia de calor, que transporta la energía térmica suministrada por un campo solar, hasta el sistema de almacenamiento térmico y/o al bloque de potencia [*Price, 2003*].

Las unidades básicas del campo solar son los módulos. Los módulos se agrupan compartiendo una serie de equipos en común, al conjunto se le denomina colector. Los módulos están unidos entre sí a través del tubo absorbedor, y su número es variable en función de las necesidades de la planta. Los colectores se agrupan para formar un lazo. El campo solar es el conjunto de Lazos de la planta de generación [*Montes et al., 2009*]. El tamaño del campo solar se determina a través del "Solar Multiplo" (SM), correspondiente a la relación entre la energía térmica producida por el campo solar, y la capacidad térmica requerida por el bloque de potencia en condiciones nominales [*Montes et al., 2009*]. Valores de SM mayor que 1 proporciona a la planta un excedente de energía térmica que permite, por un lado aumentar las horas anuales de operación aportando al bloque de potencia la capacidad térmica necesaria en periodos de baja captación de radiación solar, y por otro lado, alimentar al sistema de almacenamiento térmico, ya sea a través de tanque de sales fundidas o mediante el almacenamiento en propios los lazos del campo solar *"HTF Bufering"*.

Dentro de un lazo el fluido que circula por los tubos entra y sale por el mismo extremo en forma de bucle. Este diseño minimiza el recorrido de la tubería principal de fluido [*Valenzuela, et al., 2005*]. El lazo tiene una entrada de fluido caloportador a través de una tubería distribuidora de HTF "frío" (295 °C), que alimenta cada uno de los lazos. La salida está conectada a la tubería colectora de HTF "caliente" (393 °C) desde donde se conducirá al bloque de potencia [*Biencinto et al., 2014*].

Desde el punto de vista estructural, los módulos cilindro parabólicos se componen de cuatro elementos principales: la cimentación y la estructura soporte, el reflector cilindro parabólico, el tubo absorbedor o receptor, y el sistema de seguimiento solar [*Herrmann et al., 2008*].

Para construir la estructura de la parábola se utilizan varias técnicas, preferentemente la espacial, la de tubo soporte central *"torque tuve"*, y la denominada Eurotrough torquebox [*Dudley et al., 1994*]. Este último diseño (Eurotrough torquebox) consigue reducir las fuerzas sobre las planchas de vidrio en un factor de tres y, por consiguiente, reduce las roturas del cristal en condiciones de vientos fuertes [*NREL, 2014*].

La generación de colector Eurotrough SKAL-ET [*Lüpfert et al., 2003*], permite reducir el coste mediante reducción de peso específico, reducción de componentes, construcción in situ, reducción de mantenimiento y mejora de la rigidez del colector, y permite operar en condiciones de viento más desfavorables, aumentando la producción anual [*NREL, 2014*].

Dentro del colector solar, la misión del reflector es la de reflejar la radiación solar que incide sobre él, y proyectarla de forma concentrada sobre el tubo absorbedor situado en la línea focal del reflector. Para llevar a cabo la reflexión se utilizan películas de plata o aluminio depositadas sobre un soporte que ofrece rigidez al sistema. Estos medios soporte están fabricados en chapa metálica, plástico o cristal [*Zarza, 2002*].

El receptor lineal del colector, también llamado *"Heat Collector Element"* (HCE), es el encargado de convertir la radiación solar concentrada en energía térmica que transporta el fluido calorífero. Se encuentra ubicado en la línea focal del concentrador, sujeto a la estructura mediante unos brazos soporte. Consiste en un tubo absorbedor que a su vez está compuesto por dos tubos concéntricos: uno interior metálico, por el que circula el fluido calorífero, y otro exterior, de cristal [*Birnbaum et al., 2008*]. El tubo metálico de acero inoxidable, de 2 mm de grosor y 4 m de longitud estándar, lleva un recubrimiento selectivo que le proporciona una elevada absorción (~94%) en el rango de la radiación solar, y una baja emisividad en el espectro infrarrojo (~15%), lo que le proporciona un elevado rendimiento térmico. El tubo de cristal que rodea al tubo interior metálico tiene una doble misión, por un lado, proteger el recubrimiento selectivo de las incidencias meteorológicas, y por otro, reducir las pérdidas térmicas por convección en el tubo absorbedor [*Birnbaum et al., 2008*]. Para hacer el vacío, una vez fabricado el tubo se conecta una bomba de vacío a una pequeña toma que existe en la cubierta de vidrio (oliva de evacuación), la cual se sella cuando se ha alcanzado el vacío deseado [*Flabeg, 2014*].

Para poder concentrar sobre el tubo absorbedor la radiación solar, el colector necesita un mecanismo de seguimiento solar que orienta el colector hacia la perpendicularidad de incidencia del sol. El sistema de seguimiento más común consiste en un dispositivo que gira los reflectores alrededor de un eje. Los colectores se instalan de forma que su eje de giro quede orientado o bien en la dirección Este-Oeste, o bien en la dirección Norte-Sur principalmente en función de la ubicación geográfica de la planta de generación [*Zarza, 2002*].

ALMACENAMIENTO DE ENERGÍA TÉRMICA

Desde el punto de vista de la producción de la energía eléctrica, un sistema solar debe dar una salida estacionaria, independientemente de la variabilidad de la radiación solar [*Li, 2008*]. Para ello se hace necesario el uso de un sistema de almacenamiento, que permita al bloque de potencia trabajar de forma continua y prevenir los riesgos derivados de las oscilaciones en la radiación solar directa [*Herrmann et al., 2002*].

Dentro de los distintos sistemas existentes, la tecnología de almacenamiento en calor sensible es la más extendida. El análisis está orientado según la eficiencia, costes y disponibilidad tecnológica en la producción, acorde a los diferentes requerimientos temporales de carga [*Kearney et al., 2009*]. La capacidad térmica máxima del sistema de almacenamiento se denomina

"Thermal Energy Storage" (TES), cuyo valor corresponde al mayor número de horas continuadas que el sistema de almacenamiento puede aportar energía térmica al bloque de potencia para producción nominal.

El sistema se caracteriza porque tanto las entradas como las salidas se realizan en forma de energía térmica. La buena transferencia de calor entre el medio de almacenamiento y el fluido calorífero de transporte suele ser otro aspecto clave, así como la estabilidad de dicho material de almacenamiento. Otro elemento que se debe tener en cuenta al diseñar este sistema está relacionado con las pérdidas térmicas al ambiente, y una buena estratificación térmica [*Suárez et al., 2015*].

El volumen de inversión requerido es el factor decisivo para la elección entre las distintas alternativas técnicas posibles. Además, los tanques que contengan dichos materiales representan una parte importante en el coste final de la instalación [*Kearney et al., 2009*].

Además de los parámetros térmicos, los materiales deben ser estables, seguros, no inflamables, no tóxicos y de fácil disposición a un precio asequible [*Gil et al., 2010*]. El elemento más crítico, desde el punto de vista técnico es la densidad energética, interesando altos valores de la misma para cumplir la función requerida con un volumen mínimo [*Tamme et al., 2003*].

La sal de sodio y sal de potasio fundidas son actualmente el medio de almacenamiento más extendido, debido principalmente a los parámetros de seguridad y económicos anteriormente descritos. Estas sales fundidas a las que se añade bórax (tetra borato sódico deshidratado) obtienen propiedades eutécticas, de manera que pueden ser utilizadas en un amplio rango de temperaturas manteniendo su estado líquido, evitando su solidificación e inestabilidad en el transporte y almacenamiento de energía térmica [*Svoboda et al., 1997*], [*Siegel et al., 1992*].

La sal fundida entre 70°C y 550°C tiene la misma capacidad térmica que el agua, así como su fluidificación y transporte, manteniendo una presión de vapor y volumen regulares a altas temperaturas. Su comportamiento inerte con el agua, su alta conductividad térmica y su alta capacidad calorífica propician que el intercambio de calor entre la sal fundida y el agua tenga una alta eficiencia al utilizar turbinas de vapor para generar electricidad [*Svoboda et al., 1997*], [*Siegel et al., 1992*].

El uso de sales fundidas implica, como ventajas, el decremento del coste nivelado de la producción de electricidad, el incremento de la temperatura de trabajo, bajo coste del material, seguridad en manipulación y utilización (estabilidad mecánica y química), y reducción del coste de almacenamiento térmico respecto a otros sistemas, debido entre otros factores a su reversibilidad térmica para un elevado número de ciclos de carga y descarga [*Pacheco et al., 2002*]. Como principales desventajas se tiene la elevada temperatura de solidificación de las sales, posibilidad de disgregación de las sales en fase líquida, y mayor superficie de contacto en el sistema de transporte (mayor sección de la conducción), produciendo mayores pérdidas por incremento de la emisividad de la radiación [*Bradshaw et al., 2010*].

Dentro de esta tecnología de almacenamiento en calor sensible, los sistemas de almacenamiento térmico mejor considerados son principalmente el sistema directo de doble tanque y el sistema indirecto de doble tanque [*Kelly et al., 2006*].

El sistema directo de doble tanque está compuesto por un intercambio térmico entre un tanque a alta temperatura (tanque caliente) y otro a baja temperatura (tanque frío), con el mismo fluido transmisor. Los dos tanques están aislados térmicamente de tal manera que el volumen de cada uno sea tal que pueda contener la totalidad del fluido de trabajo. Durante la carga, se llena el tanque caliente con el fluido de trabajo procedente del campo solar, y se vacía el tanque frío, de donde sale el fluido que alimenta el campo solar. Durante el proceso de descarga, el fluido del tanque caliente cede su energía al bloque de potencia para posteriormente introducirse en el tanque frío.

El sistema indirecto de doble tanque se basa en el intercambio térmico entre distintos fluidos, un fluido de transferencia y un fluido de almacenamiento, mediante sistemas de serpentín forzado. Este sistema de doble tanque sin intercambio másico complementa al anterior sistema, de doble tanque directo, permitiendo la generación directa de electricidad desde el campo solar a través de intercambiadores, y reconduciendo los excedentes térmicos de radiación solar a los tanques de almacenamiento térmico. El sistema indirecto de doble tanque permite mejorar el rendimiento global de la instalación al reducir las pérdidas térmicas de almacenamiento cuando se trabaja en generación directa, circunstancia habitual cuando el campo solar es capaz de mantener al bloque de potencia operando a la carga preestablecida.

MERCADOS DE LA ELECTRICIDAD

A nivel global, las empresas eléctricas han estado tradicionalmente integradas de forma vertical. Una misma empresa se encarga de todas las etapas del sistema, es decir, generación, transmisión, distribución y comercialización de la energía [*Marulanda, 2004*]. Estas compañías, de propiedad privada o pública, coexistían frecuentemente con compañías distribuidoras independientes, pero formando un monopolio al ser consideradas como un servicio público. Bajo este esquema, gran parte de las maniobras de generación, operación y planificación de los sistemas eléctricos es controlada por un organismo centralizado (operadora central) [*Amundsen et al.,* *1998*], que asegure el suministro y supervisión de la calidad del servicio eléctrico.

En el año de 1982 se produce en Chile una nueva forma de ver las compañías eléctricas al crear un "*pool*" de energía en competencia (conjunto de aportes o posiciones individuales para conformar el total de la energía consumida/generada) tras privatizar mayoritariamente el sector [*Vargas et al., 2001*]. Muchos países han adoptado este modelo de organización para sus industrias eléctricas, incluyendo España (1998) [*Arocena, 1999*], separando los procesos de generación, transmisión y distribución. Se sustituye el operador central por un mercado que obedezca las leyes de libre competencia. Bajo este nuevo esquema, emergen agentes como las compañías generadoras, comercializadoras, distribuidoras y sobre todo dos operadores independientes; el Operador del Mercado Eléctrico (OMEL) tiene por función coordinar las transacciones económicas entre los diversos agentes que intervienen en el mercado para España [*OMEL/OMIE 2014*], y un segundo operador de sistema que tiene a su cargo el cuidado, administración y explotación de las redes eléctricas así como la calidad del servicio, como es el caso de Red eléctrica de España (REE) [*Díaz et al., 2015*].

El mercado de generación tiene como principal objetivo motivar la competencia entre los generadores y reducir el precio de la energía eléctrica al consumidor [*Olivares, 2014*]. Los esquemas implantados en los mercados intentan establecer el precio con una antelación suficiente, a partir de mecanismos de subasta donde los agentes (generadores y consumidores) declaran libremente los precios ofertados [*Post et al., 1995*].

El modelo tipo "*Pool*" (*Power Pool*) es el más extendido para organizar los mercados eléctricos liberalizados, donde la compra y venta de energía es valorada y determinada por un organismo independiente, basándose en una optimización de los costes totales del sistema [*Ferrero et al., 1998*]. Para ello, generadores y consumidores emiten ofertas o curvas de costes al operador del mercado. El plan de generación obtenido mediante casación se transfiere al operador del sistema, quien verifica la factibilidad técnica del mismo. En este modelo el precio de la energía generalmente se determina por medio de un despacho económico centralizado *"Economic Dispatch + Unit Commitment"* [*Johnson et al., 1997*].

Por su parte, los mecanismos de subasta existentes en los mercados eléctricos no contemplan la administración de los recursos energéticos de forma centralizada, como por ejemplo los mercados de España y de Inglaterra y Gales [*Canoyra, 1998*][*Rahimi, 1999*], transfiriendo esta gestión a las compañías de generación. Así, estas compañías utilizan modelos matemáticos para realizar la casación entre las ofertas de compra y venta de energía que realizan los agentes del mercado, incluyendo en el modelo las restricciones que caracterizan las centrales de generación.

De igual modo, en los mercados no regulados las compañías generadoras no tienen obligación de servicio. Para maximizar el beneficio como producto de la venta de su energía eléctrica, dichas compañías elaboran sofisticadas estrategias de oferta que garanticen este objetivo [*Kumar et al., 2011*]. Es por ello que resulta necesaria por parte de las compañías generadoras la determinación de una estrategia óptima de oferta de venta en el mercado mayorista de energía. Esta depende de varios factores tales como el tamaño de la compañía, el tipo de tecnología de generación, el precio de la energía eléctrica en el mercado, el comportamiento de la demanda y las restricciones técnicas de las centrales de generación. Como resultado de los procesos anteriores, el programa resultante es el denominado Programa Horario Operativo (PHO), que establece la energía que debe suministrar cada planta generadora [*Arocena, 1999*][*Canoyra, 1998*] [*OMEL/OMIE, 2014*] [*REE Proc., 1998*].

A nivel global, existen proyectos para el acoplamiento en precio de los Mercados diarios de energía dentro de la Unión Europea que se dividen en dos grandes grupos, zona noroeste de Europa (NWE) y zona suroeste de Europa (SWE). Se ha establecido un proceso completo de pruebas, con fecha de inicio mayo de 2013, utilizando la solución *"Price Coupling of Regions"* (PCR) [*Glachant, 2010*]. Desde esta fecha, el mercado diario del Mercado Ibérico de Electricidad (MIBEL) [*Salvador, 2010*] está acoplado en precios con el de centro-norte de Europa. Esto supone que el MIBEL utiliza el mismo algoritmo para resolver la casación, *Euphemia* [*Newbery et al., 2016*], y que la capacidad de interconexión España-Francia, comercialmente disponible de acuerdo a los respectivos operadores del sistema REE y *"Réseau de Transport d'Électricité"* (RTE) [*Späth & Scolobig, 2017*], se asigne de forma implícita en dicho mercado.

La implantación del proyecto PCR representa un importante avance hacia un mercado diario de electricidad armonizado en el continente, con un aumento esperado de la liquidez, la eficiencia y el bienestar social [*Mastropietro et al., 2015*].

OPTIMIZACIÓN DE LA OPERACIÓN EN PLANTAS CON TECNOLOGÍA DE COLECTORES CILINDRO PARABÓLICOS

Los procesos de modelado y optimización de plantas de generación eléctrica mediante tecnología de colectores cilindro parabólicos ya han sido abordados previamente por la literatura existente, considerando tanto procesos térmicos genéricos como procesos más concretos, atendiendo a sistemas específicos de la instalación.

Así, en [*El Hefni, 2015*], se presenta un modelo para plantas genéricas de concentración solar, mediante el uso de las ecuaciones de conservación de la masa y la energía. En [*Usaola, 2012*], se presenta un método de optimización para plantas genéricas solares de concentración. Este trabajo tiene por objeto mejorar los beneficios de la venta de la energía generada dentro de un mercado liberado. A pesar de ello, la optimización propuesta parte de una hipótesis genérica de operación y funcionamiento de planta solar, que no se ajusta, por tanto, a las características técnicas inherentes a las plantas de colectores cilindro parabólicos.

Por su parte, en [*Sioshanshi, 2010*] un modelo de optimización es usado para calcular el ajuste de costes de implantación considerando diferentes hipótesis y modos de operación. Sin embargo, en este trabajo no se describe ni se valida la relación entre la planta real y el modelo generado. En [*Martin, 2013*], se presenta un modelo matemático para la optimización de planta. Este trabajo se centra en la mejora del bloque de potencia a través del desarrollo de un ciclo de Rankine regenerativo. En [*Kumanresan, 2012*] y [*Reddy, 2012*], se realiza un estudio de operación de planta, donde se trabaja en la minimización de las pérdidas de calor en los diferentes sistemas mejorando así la eficiencia de los mismos. Del mismo modo, en el modelo de optimización descrito en [*Wittman, 2011*], se describe la formulación correspondiente a los parámetros físicos de la planta. No obstante, no se describe la metodología seguida para el proceso de optimización, ni el estudio abarca un ciclo anual de resultados, mostrando únicamente la energía entregada a red en periodos puntuales de 24 horas. En [*Porras, 2010*], se abarca el estudio de la planta en días con radiación solar. Sin embargo, no presenta la formulación aplicada en el modelo de optimización, ni realiza un análisis comparativo de los beneficios obtenidos. En [*Garcia, 2011*], con el objeto de estimar la producción neta puntual de electricidad, se desarrolla un modelo de simulación de operación de planta, donde los resultados fueron comparados con valores reales de generación eléctrica. No obstante, este trabajo no aborda un estudio a largo plazo ni contempla el comportamiento del mercado eléctrico.

En lo referente al análisis tecno-económico de este tipo de tecnología, en [*Guédez, et al., 2014*] se presenta un análisis de planta con almacenamiento térmico y su integración dentro del mercado eléctrico. El estudio se basa en la evaluación del coste promedio de la electricidad *"Levelized Cost of Electricity"* (LCOE) donde los resultados son comparados con una central equivalente de ciclo combinado. En [*Casati, 2015*], se presenta un modelo de planta con almacenamiento térmico mediante doble tanque de sales fundidas, dentro de un mercado eléctrico con precios variables. A pesar de ello, en este trabajo no se analiza el comportamiento del mercado eléctrico no regulado, ni se propone un análisis comparativo de comportamiento del modelo entre mercados eléctricos regulados y no regulados.

Otros trabajos analizan la operación de planta y su optimización acorde al lugar de implantación. En [*Abdul Baseer, 2018*], se presenta un modelo de optimización de operación de planta para Oriente Medio, donde se analiza el LCOE en relación a la potencia eléctrica neta generada. Del mismo modo, en la literatura aparecen estudios para Argelia [*Boukelia, 2015*], Grecia [*Poullikkas, 2009*], India [*Bishoyi, 2017*] y Egipto [*Shouman, 2015*]. Todos ellos desde un punto de vista de operación de planta acorde a las características de radiación y cobertura, como niebla y arena en suspensión, de cada localización en particular.

MOTIVACIÓN Y METODOLOGÍA

Investigar es ver lo que todo el mundo ha visto, y pensar lo que nadie más ha pensado
ARTHUR SCHOPENHAUER
PARERGA Y PARALIPÓMENA. PIEZA 76

La revisión de la literatura especializada referente a centrales termosolares de concentración mediante tecnología de colectores cilindro parabólicos se ha centrado en los diferentes modelos, diseños y estructura final de plantas, teniendo como premisas su ubicación geográfica, tamaño del campo solar, capacidad de generación térmica, sistema de almacenamiento de energía integrado, capacidad de generación eléctrica y sistemas de control de planta.

Se presta especial atención a la ausencia de trabajos existentes que profundicen en el análisis conjunto de las proporciones óptimas de dimensionado del campo solar, tipo y sistema de almacenamiento térmico y modos de operación y volcado a red de la planta, independientemente de su ubicación, tipo de mercado eléctrico en la que se enmarca y capacidad de generación. Siendo esta, por tanto, la base de este trabajo investigación.

Así, se plantea como motivación principal de este trabajo el estudio de alternativas viables, de carácter innovador y relevantes a la configuración estándar de las plantas termosolares de concentración mediante la tecnología de colectores cilindro parabólicos, tanto a nivel de implementación como a modo de operación, que favorezcan la optimización de la generación de energía y del volcado a red.

Este trabajo se inicia con el estudio y una serie de visitas técnicas a diferentes plantas termosolares de la geografía española, dentro de las tecnologías de colectores cilindro parabólicos y de receptor central. La principal planta a estudio es la central de generación mediante colectores cilindro parabólicos "La Africana" situada en la localidad de Posadas (Córdoba). Dadas las restricciones del mercado eléctrico español todas estas plantas tienen una capacidad de generación eléctrica igual o menor de 55 MW_e brutos. De igual modo, todas las plantas estudiadas incorporan un sistema de almacenamiento de energía térmica mediante doble tanque de sales fundidas, variando su capacidad entre 3 y 7,7 horas de producción equivalente acorde a las características de cada planta.

Un segundo estadio abarca la revisión bibliográfica. El análisis de los diferentes trabajos de investigación que, por su actualidad y relevancia, tienen especial significación sobre el tema a tratar en este trabajo. Una vez analizadas tanto las características técnicas como de operación de plantas con tecnología de colectores cilindro parabólicos, incluyendo almacenamiento de energía así como los avances actuales significativos en este campo, se identificación de las áreas de trabajo aún no abordadas, que posibilitan el desarrollo de este trabajo y sustentan esta Tesis Doctoral.

Posteriormente se ha diseñado y construido un modelo de planta con almacenamiento de energía mediante doble tanque de sales fundidas, quemador de gas para precalentado de aceite sintético, e intercambiador de calor aceite-sales fundidas-vapor, equivalente a la planta real en estudio, para la posterior verificación y calibración del modelo. Este modelo de planta se implementa haciendo uso de los bloques termodinámicos Thermolib® elaborados para un entorno en Matlab (MATLAB R2010A®).

A continuación, la herramienta *"linprog"* dentro de la versión Simulink V2010 de Mathlab®, permite la simulación mediante programación lineal del modelo acorde a cada parametrización realizada considerando variables geográficas, ambientales constructivas, de operación de planta y comportamiento del mercado eléctrico.

La primera parte del proceso de simulación se basa en recrear el entorno de funcionamiento de la planta en estudio "La Africana". Una vez parametrizada la planta y obtenidos los datos de simulación, se valida y calibra el modelo generado. Posteriormente se establecen dos bloques principales de trabajo en función del sistema de almacenamiento de energía utilizado. Por un lado la planta con almacenamiento con doble tanque de sales fundidas, y por otro lado almacenamiento en el sistema de aceite de los colectores mediante mayoración del campo solar.

Los resultados obtenidos por las simulaciones dentro de cada bloque de trabajo son analizados obteniendo los valores que optimizan cada variable dentro de la función. Posteriormente se realiza un análisis comparativo de las funciones óptimas para cada bloque de trabajo y parametrización. Este análisis final permite definir con precisión el tamaño del campo solar así como el tipo, dimensionado y comportamiento del sistema de almacenamiento de energía, además del modo de operación de planta, acorde a cada ubicación, condiciones climáticas concretas y tipo de mercado eléctrico.

El análisis y estudio de los entornos diseñados y modelados forman la base de los trabajos que sustentan la presente Tesis Doctoral. De igual modo, algunos de los resultados obtenidos, como *"HTF Buffering"*, se encuentran actualmente implementados en plantas reales en operación.

En la Figura 1 se representa un resumen gráfico de la estructura metodológica seguida en el proceso de investigación. Por su parte, la Figura 2 muestra el organigrama desarrollado como soporte a la recreación del entorno de funcionamiento, el análisis del modelado, y secuenciación del proceso de simulación para operación mediante almacenamiento de energía térmica en el campo solar "*HTF Buffering*", referidos a la Planta "La Africana".

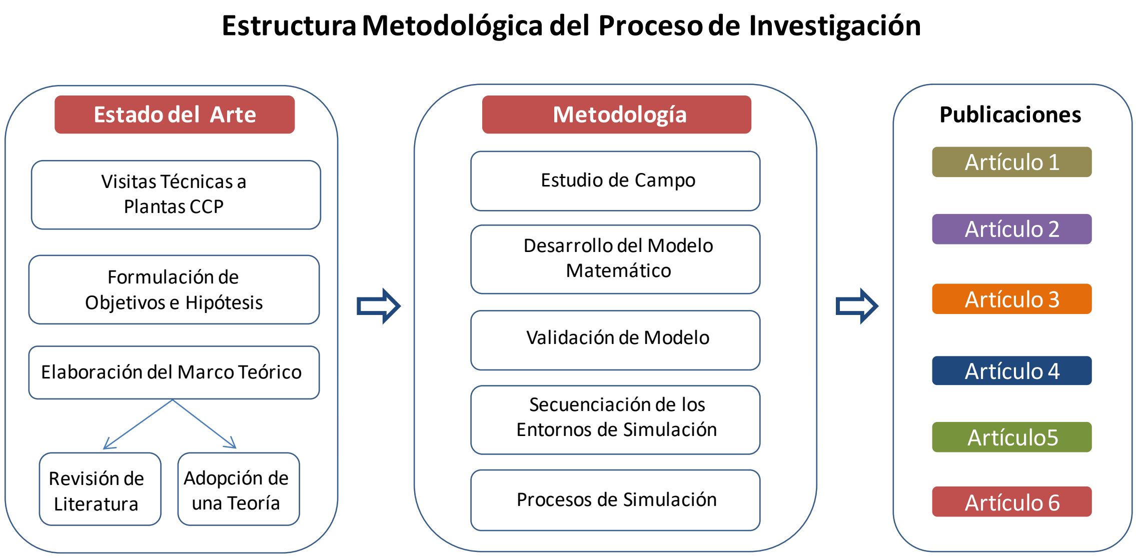

Figura 1. Estructura metodológica seguida durante el proceso de investigación.

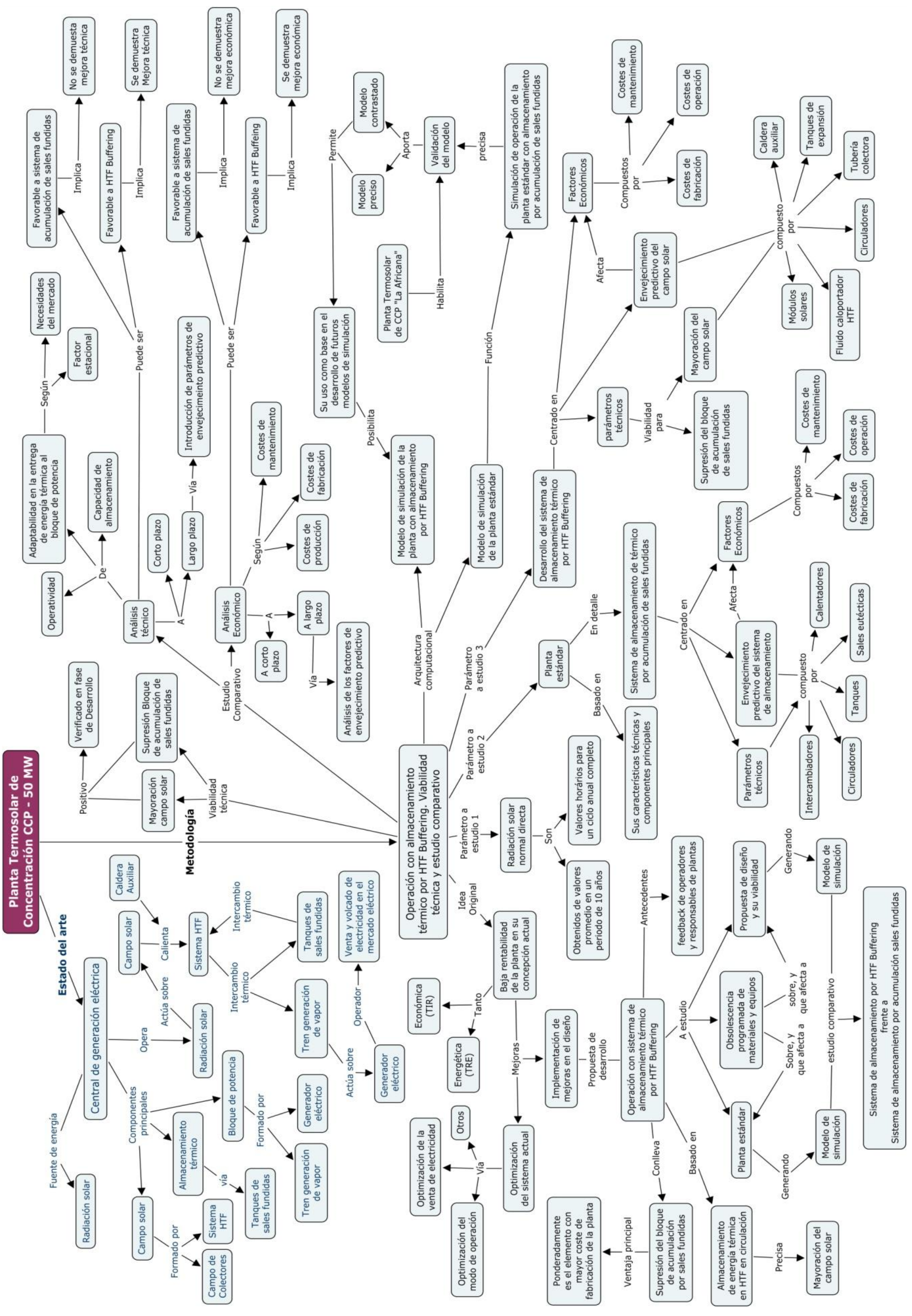

Figura 2. Operación con almacenamiento térmico por "HTF Buffering". Viabilidad técnica y estudio comparativo.

HIPÓTESIS Y OBJETIVOS

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VIRGILIO
GEÓRGIAS. LIBRO II, 490

Las hipótesis de trabajo de esta Tesis se basan en que la optimización de operación de una planta de generación eléctrica mediante la tecnología de colectores cilindro parabólicos, a través de un modelo matemático que englobe el recurso solar, el dimensionamiento del campo de colectores, capacidad de almacenamiento de energía térmica y tipo de mercado eléctrico, puede optimizar los costes de implantación de este tipo de tecnología, así como maximizar la producción y los beneficios de venta de energía eléctrica.

Una vez planteadas las hipótesis de trabajo, el establecimiento de unos bloques de objetivos generales y específicos se presenta como factor fundamental que aporta orden y estructura a la presente Tesis Doctoral.

La investigación se centra en la optimización del funcionamiento y operación de las plantas termosolares con sistema de colectores cilindro parabólicos dentro de la tecnología de receptor central, independientemente de su capacidad de generación y de la ubicación geográfica donde se encuentre.

Se parte, por tanto, del análisis de una planta ya existente y en funcionamiento, concretamente una planta termosolar con 55MW$_e$ de potencia bruta y almacenamiento térmico mediante doble tanque de sales fundidas.

Se analiza a nivel técnico y económico el dimensionamiento del campo solar, así como diferentes sistemas de almacenamiento de energía y su capacidad, factores que permiten aumentar la generación de energía además de adaptarse en cada momento al mercado tipo existente. De igual modo, se profundiza en el modo de operación de la propia planta, se analiza la venta de energía y volcado a red, y se estudia de la bibliografía actual y relevante. De todo ello, se obtienen a modo de objetivos los aspectos susceptibles de ser abordados en este trabajo.

Así, los objetivos, general y específicos planteados en este proyecto son:

Objetivo general

Mediante el aporte de elementos innovadores, el desarrollo de un modelo de optimización que simule y valide las diferentes hipótesis de trabajo planteadas, y el análisis técnico y económico de los resultados obtenidos, se presenta como objetivo general de la presente investigación el dimensionado y operación óptimos de las plantas termosolares con tecnología de colectores cilindro parabólicos, que permita el mayor nivel de eficiencia tecno-económica, considerando como variables principales el lugar de implantación, dimensionado del campo solar, almacenamiento de energía térmica y tipo de mercado eléctrico.

Objetivos Específicos

1. Estudiar la tecnología, el diseño, las características de componentes y montaje, y el modo de operación de las plantas termosolares con tecnología de colectores cilindro parabólicos.

2. Analizar el modo de operación referente a la de venta de energía eléctrica y de volcado a red.

3. Indagar en los sistemas de almacenamiento de energía para este tipo de tecnología, así como buscar alternativas viables a los sistemas ya existentes.

4. Establecer, calibrar y validar un modelo de simulación de planta que permita el análisis de las diferentes configuraciones de planta y modos de operación planteados.

5. Analizar los costes de implantación de la planta, así como los propios de mantenimiento y operación para cada hipótesis planteada.

6. Obtener el dimensionado y operación de planta óptimos acorde a parámetros técnicos y económicos. Parámetros técnicos como el lugar de implantación, la superficie del campo solar, el tipo y capacidad del sistema de almacenamiento de energía y las necesidades de generación eléctrica. Parámetros económicos como el factor de capacidad y el coste promedio de la energía.

7. Obtener el dimensionado de planta, operación de planta y operación de mercado óptimos acorde al tipo de mercado de la electricidad. Mercado eléctrico regulado o mercado eléctrico no regulado.

ESTRUCTURA DEL TRABAJO

La técnica: el esfuerzo para ahorrar esfuerzo
JOSÉ ORTEGA Y GASSET
MEDITACIÓN DE LA TÉCNICA. CAPÍTULO III

El presente trabajo de Tesis Doctoral se fundamenta en seis artículos de investigación que se presentan a continuación. En todos ellos se ha tomado como base de trabajo una planta CCP actualmente en funcionamiento con una potencia neta máxima de generación eléctrica de 50 MW_e, siendo éste el tamaño máximo de planta de generación que permite para régimen eléctrico especial en España. Así, el estudio de casos presentado en los artículos 1, 3, 4 y 5, se centra en una planta de 50 MW_e, debido a que están contextualizados dentro del sistema de generación español. No obstante, en los artículos 2 y 6 se opta por el estudio de dos plantas de 50 MW_e en paralelo (100 MW_e) con el objeto de acercar el estudio a un tamaño de planta más común en el ámbito internacional.

En el **Artículo 1** se analiza la energía solar térmica de concentración desde un punto de vista de parametrización, potencia generada, y beneficio de la venta de la energía eléctrica, considerando tres sistemas diferentes de almacenamiento de energía térmica para una planta CCP de 50 MW_e.

A través de estudio de los diferentes sistemas que componen este tipo de tecnología, como son la ubicación, dimensionado, sistema de almacenamiento y la energía eléctrica generada, se presenta una primera aproximación al modelo de optimización haciendo uso de las ecuaciones obtenidas en la etapa de análisis y estudio de la Tesis.

Dentro de la metodología de este artículo se presentan tres diferentes configuraciones de planta, planta sin almacenamiento térmico, planta con almacenamiento térmico mediante doble tanque de sales fundidas, y planta con almacenamiento térmico en el campo solar mediante dos depósitos de aceite sintético *(Overflow system)*.

Los resultados mostrados en este trabajo muestran los puntos óptimos de potencia eléctrica generada, así como los beneficios obtenidos de su venta dentro de un mercado eléctrico regulado, considerando cada uno de los sistemas de almacenamiento propuestos.

El **Artículo 2** se enfoca en la búsqueda de la configuración óptima de planta, acorde al lugar de implantación y a la capacidad de almacenamiento térmico como variables de decisión. Para ello, cuatro localizaciones geográficas son consideradas, representando cuatro niveles de radiación normal directa de 5, 6, 7 y 8 kWh/m^2 respectivamente.

Con el objeto de tener una base común de comparación, el estudio parte de una planta de 100 MW_e, con un solar múltiplo en el campo de colectores constante e igual a 1,7. El sistema de almacenamiento se realiza mediante doble tanque de sales fundías, con una capacidad variable de 1 a 7 horas equivalentes de producción a plena carga.

En este trabajo se realiza el análisis comparativo entre la potencia eléctrica generada y la energía térmica proveniente del campo solar que entra en el tanque caliente, en función de la capacidad del sistema de almacenamiento. Los resultados ofrecen el dimensionamiento óptimo del sistema de almacenamiento que maximiza la producción de electricidad para cada escenario de radiación considerado.

Dentro del **Artículo 3** se presenta un análisis sobre la viabilidad de integración de las energías renovables en los mercados eléctricos no regulados. Se parte del estudio del estado del *"mix"* energético español, su evolución desde 1998 hasta 2014, y una prospectiva para producir el 100% de la demanda energética mediante recursos renovables.

Por su parte, la libre venta de energía eléctrica se establece como modelo representativo de la dirección que en esta materia toma el sistema común europeo. La evolución de este tipo de mercado se produce desde un sistema con precios de electricidad preestablecidos hasta un mercado libre a través de la desregulación de la venta de electricidad.

Este artículo se centra en la tecnología CCP, en el estudio de los costes de operación, y en la viabilidad de explotación de esta tecnología dentro de mercados no regulados de venta de electricidad. Se toma como base de trabajo una planta de 50 MW_e de producción neta con sistema de almacenamiento térmico usando doble tanque de sales fundidas. En este sistema, tanto el dimensionamiento del campo solar como el tamaño del sistema de almacenamiento son constantes.

El estudio se realiza tomando dos tipos de precios de venta de electricidad respecto al precio medio de la misma a lo largo del año, alto o superior, y bajo o inferior, acorde a la estructura del mercado eléctrico. Así, las variables de decisión consideradas en este trabajo son la energía enviada al sistema de almacenamiento, volcado a red desde el campo solar y volcado a red desde el sistema de almacenamiento.

Los resultados obtenidos representan la operación óptima de mercado que maximiza los beneficios, acorde a los parámetros y variables establecidos, tanto para periodos con precios bajos como para precios altos de venta de electricidad.

En el **Artículo 4** se analiza la gestión de las plantas termosolares de concentración con tecnología CCP. Frente a los sistemas tradicionales de almacenamiento de energía térmica en este tipo de plantas, principalmente almacenamiento mediante doble tanque de sales fundidas, el bloque principal de este artículo se centra en la presentación de un innovador sistema de almacenamiento de energía térmica en el campo solar mediante la circulación del aceite sintético dentro del sistema de colectores, denominado *"HTF Buffering"*.

El almacenamiento de energía térmica a pequeña escala en el campo de colectores, es práctica común en el funcionamiento diario de la planta. Por un lado, para mantener una adecuada temperatura del aceite sintético que circular por los colectores permitiendo una pronta puesta a punto y entrada en régimen de la planta principalmente en periodos de cobertura parcial o total del campo solar. Por otro lado, como apoyo térmico para mantener la temperatura de las sales fundidas dentro del tanque de almacenamiento acorde a un rango de temperatura que evite su solidificación.

El almacenamiento de energía térmica a gran escala dentro del campo solar se realiza mediante la mayoración del mismo. Por tanto, para estudiar la viabilidad del sistema propuesto, se realiza un análisis tecno-económico de operación de una planta 50 MW_e. El modelo propuesto se ha estudiado dentro de un mercado eléctrico regulado para la obtención de resultados directos sin la influencia de las variaciones propias del mercado no regulado. Está compuesto por el campo solar, apoyo al campo solar mediante quemador de gas y bloque de potencia.

El dimensionamiento óptimo del campo solar vendrá dado por el valor de múltiplo solar que ofrezca una mayor generación de energía eléctrica a un menor coste promedio de la energía producida. Estos resultados, junto al análisis del factor de capacidad del sistema propuesto, permite la comparación tanto con otros sistemas de almacenamiento, como con otras tecnologías de generación eléctrica mediante energías renovables.

Dentro del **Artículo 5** se presenta un estudio profundo a nivel de operación de planta para un mercado no regulado. Para ello, el modelo se centra en el análisis de una planta de 50 MW_e con almacenamiento de energía térmica mediante doble tanque de sales fundidas.

Con el objeto de establecer una base sólida que permita la comparación de resultados, se toma como valores constantes la localización de la planta solar, el dimensionado del campo solar y el tamaño del sistema de almacenamiento mediante sales fundidas. De igual modo, se establece el sector eléctrico español como sistema eléctrico tipo.

Las variables consideradas en este estudio son por un lado la disponibilidad de recurso solar, y por otro el comportamiento del mercado eléctrico a través del precio de la electricidad. Se consideran por tanto cuatro posibles casos de estudio a través de la combinaciones dadas de las dos variables anteriormente descritas. Siendo "baja radiación solar" y alta radiación solar" los factores para la variable recurso solar. Y por otro lado "precios elevados" y "precios bajos" los factores para el comportamiento del mercado eléctrico.

El entorno de simulación proporciona resultados para las 8760 horas pertenecientes al ciclo completo de un año tipo. En este artículo se muestran los resultados de generación óptima acorde a cuatro intervalos seleccionados de 72 horas representativos de los cuatro escenarios más frecuentes de operación de la planta solar.

Para cada caso de estudio, la comparativa entre los resultados de operación mediante generación algebraica directa y los procedentes del modelo de optimización desarrollado, muestran tanto la evolución en generación neta de energía eléctrica, como la mejora en los beneficios de venta brutos obtenidos.

En el **Artículo 6**, a través del análisis combinado de gestión y operación de planta, se estudia la viabilidad y sostenibilidad de este tipo de tecnología acorde a las premisas de recurso solar y mercado de la electricidad.

El modelo se enfoca en el estudio de una planta termosolar de 100 MW_e. La planta incluye campo solar, quemador de apoyo, almacenamiento térmico mediante doble tanque de sales fundidas y bloque de potencia.

Se estudian tres localizaciones diferentes, representando la disponibilidad de recurso solar acorde a baja, media y alta radiación directa. De igual modo, para cada uno de los escenarios geográficos descritos, la optimización de gestión de planta se lleva a cabo considerando mercados eléctricos regulado y no regulado. En relación a la gestión de planta, los factores de configuración tomadas para el estudio son el dimensionamiento del campo solar y el tamaño del sistema de almacenamiento.

Para cada escenario de radiación, el análisis de la generación de energía eléctrica permite obtener el valor de almacenamiento térmico óptimo para cada valor de solar múltiplo. Con los datos previos de generación y almacenamiento óptimos para cada valor de solar múltiplo, el análisis del coste nivelado de la energía frente a dicho punto óptimo de producción, proporciona la configuración de campo solar que maximiza la eficiencia de tecno-económica de la planta.

Finalmente se realiza un análisis económico de los resultados anteriores tanto para mercado regulado como no regulado. Se evalúa la relación entre los costes anuales de inversión y el beneficio medio anual bruto de operación de planta y venta de energía eléctrica.

Para la configuración óptima de planta dentro de un mercado eléctrico regulado, existe elevada linealidad entre los resultados procedentes del análisis del coste nivelado de la energía y los resultados económicos. Se constata así que el LCOE es el mejor factor de referencia para este tipo de mercados.

En lo referente a un mercado eléctrico no regulado, la operación y venta de la energía eléctrica generada permite buscar puntos de trabajo óptimos donde se favorece la mayor capacidad de almacenamiento térmico, así como la disponibilidad de volcado a red en periodos de precios elevados de venta de la energía eléctrica. El coste nivelado de la energía deja de tener, por tanto, un carácter tan representativo para la configuración óptima de planta en este tipo de mercado.

En la Figura 3 se muestra un cuadro resumen de la actividad de investigación llevada a cabo. Se puede observar, por tanto, la relación existente entre los diferentes parámetros analizados de la planta solar durante el desarrollo de la investigación, los objetivos alcanzados a través de las mejoras tecno-económicas abordadas, y los resultados obtenidos en forma de publicaciones.

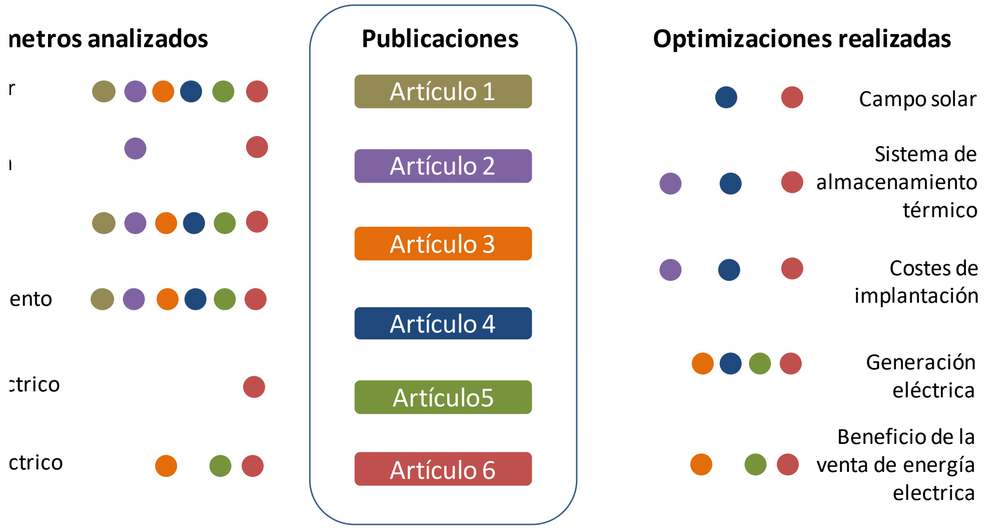

Figura 3. Relación entre los parámetros de planta analizados en el trabajo de investigación, las optimizaciones realizadas, y los resultados obtenidos en forma de publicaciones científicas.

ARTÍCULO 1

OPTIMAL MODELS FOR CONCENTRATING SOLAR POWER PLANTS BY STORAGE AND OVERFLOW SYSTEMS

In Proceedings of Mixgenera 2011, Options for the Future, Madrid, Spain, 17 November 2011; UC3M: Madrid, Spain, 2011; 1-4.

Abstract

Concentrating Solar Power Systems (CSP) is a promising future technology using solar renewable resources in medium and high power generation plants.

The thermal storage technology provides a competitive source of electricity generation with renewable energy rather than established fossil fuels. This is so even when the contribution to auxiliary services from fossil resources is taken into account. In this work, different mathematical models are shown, as well as different ways of management of the thermal energy obtained from the solar field are compared.

Some parameters such as dimensions, location and total production of electricity are configured in optimization models in order to compare the different technologies from an economical point of view.

Resumen

Los sistemas de energía solar por concentración (CSP) se presentan como una tecnología de futuro, que utiliza recursos solares renovables en plantas de media y alta generación de energía eléctrica.

Del mismo modo, la capacidad de almacenamiento térmico proporciona una fuente competitiva de generación de electricidad con energía renovable en lugar de combustibles fósiles. Esto es así incluso considerando la contribución a los servicios auxiliares procedentes de los recursos fósiles. En este trabajo, se muestran diferentes modelos matemáticos, así como diferentes formas de gestión de la energía térmica obtenida del campo solar.

Algunos parámetros como las dimensiones, la ubicación y la producción total de electricidad se configuran en modelos de optimización con el fin de comparar las diferentes tecnologías desde un punto de vista económico.

MixGenera 2011

Options for the future

November 17, 2011.
Auditorium of the University Carlos III de Madrid
Leganés, Madrid, Spain.
http://electrica.uc3m.es/mixgenera/

The Energy Mix at the years 2020 y 2030

ISBN: 978-84-614-9978-6

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Optimal Models for Concentrating Solar Power Plants by Storage and Overflow Systems

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***Abstract*— Concentrating Solar Power Systems (CSP) is a promising future technology using solar renewable resources in medium and high power generation plants. The thermal storage technology provides a competitive source of electricity generation with renewable energy rather than established fossil fuels. This is so even when the contribution to auxiliary services from fossil resources is taken into account. In this work, different mathematical models are shown, as well as different ways of management of the thermal energy obtained from the solar field are compared. Some parameters such as dimensions, location and total production of electricity are configured in optimization models in order to compare the different technologies from an economical point of view.**

***Index Terms*— Concentrating solar power, Energy storage, Implementation cost, Optimization.**

I. INTRODUCTION

CONCENTRATING Solar Power Systems (CSP) have been the most promising renewable energy resources for the last ten years, after other technologies have been established.

European directives such as 2001/77/EC (promotion of electricity generated from renewable energy in inner electricity market) [1] have outlined for the last years research work of technicians and departments related with renewable energies, and more specifically with solar thermal energy and electricity production. So, solar reception technology has developed new models and architectures able to best obtain the necessary amount of solar energy in smaller surfaces. Nowadays, the generation of electricity by renewable resources from solar energy and its integration in the electrical market depend on solar availability. The development of thermal storage systems lets the projection of solar thermal systems increase in order to generate electricity, and also locate them as renewable energy systems able to meet the requirements of electricity consumption.

The selection of parameters and specific variables such as storage capacity, reception surface or generation systems lead us to propose some specific optimization enouncements and to obtain high efficiency proposals for optimal operation. Benefit and cost have been considered here to obtain the best solution and operation availability.

II. SOLAR THERMAL PLANTS AND THERMAL ENERGY MANAGEMENT

Solar reception in CSP is mainly performed in infrared spectrum. The thermal exploitation by active transmission fluid in medium temperature (from 200ºC to 600ºC), and concentration by CTS (Concentrating Thermo Solar Systems) include a large array of technological families, which can be categorized according to the way they focus the sun rays as well as the technology used to receive solar energy [2].

One of these technologies, parabolic troughs (line focus, mobile receiver), consists of parallel rows of mirrors (reflectors) curved in one dimension to focus sunrays. The mirror arrays can be more than 100m long with the curved surface 5m to 6m across. Stainless steel pipes (absorber tubes as heat collectors) have a selective coating that is designed to allow pipes to absorb high levels of solar radiation while emitting very little infra-red radiation. The pipes are isolated by an evacuated glass envelope. The reflectors and the absorber tubes move both following the sun with one degree of freedom (North-South axes). This is the most usual solution for medium investment cost. That is the reason why this is the main technology used in our model to optimize the production of electricity with thermal storage.

Three possible configurations are found in these power systems depending on the management of the thermal energy obtained from the solar field before it is used by the power block [3].

The first one is to consider direct generation without either thermal storage or buffer solution. In this case all the thermal energy obtained from the solar field is directly driven to the power block and then used to generate electricity. When the solar resource produces overheating in the solar field, the only solution is the partial fadeout of collectors that defocuses them and so reduces the solar collection. This option is more frequent when the solar resource along the yearly period is enough to produce electricity during fifteen or more hours per day in average.

The second one is to consider the use of a molten salt double-tank as thermal storage systems into CSP plants, as shown in figure 1. The Double Tank Direct System (thermal exchange between two tanks HT/LT with the same thermal transmission fluid) lets to divert excess heat to a thermal storage material during the day. When production is required after sunset, the stored heat is released into the steam cycle and the plant continues producing electricity. Sodium and potassium molten salt is currently one of the most efficient thermal storage materials in medium temperature concentration solar thermal plants. Molten salt mechanical and chemical stability reduces storage cost above 65% and it also increases thermal reversibility related to other thermal storage systems [4]. The high efficiency of the heat exchange with water allows the use of these salts to transport solar heat to produce water steam. The expansion of the steam in conventional turbines makes the electricity production available. The solidification point of these salts makes them less useful in solar fields and pipes, making the synthetic oil the most common resource.

The double-tank direct system increases the complexity of installation and therefore its implementation costs. The whole efficiency of this double-thermal exchange system (synthetic oil in the solar field, molten salt in storage and steam in the power block) is lower than the single-thermal exchange system (synthetic oil in the solar field and steam in the power block). Nevertheless, the double-tank system is a frequent solution either when the solar resource is not enough to obtain the average production of fifteen hours per day in one yearly period, or when the production of electricity needs adaptation to the free market electricity prices (without prices regulation or pool distribution).

The last option is to consider the possibility of increasing the capacity of the overload tanks placed within the thermal fluid transport circuit. These overload tanks are designed to control the volume and pressure of this thermal fluid. With this solution, thermal exchange is used for only two materials such as synthetic oil for solar field, and steam for power block.

The schema in figure 2 shows the intermediate solution with lower implementation costs than the standard double-tank direct system, which is more adapted to market requirements and independent from the solar resource [5].

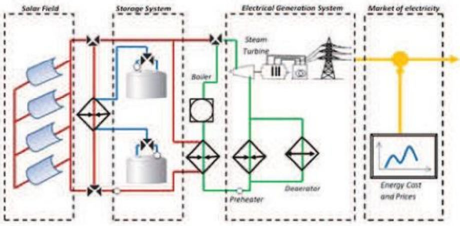

Fig. 1. Solar Thermal Plant with double tank storage system and oil-salt-steam thermal exchange.

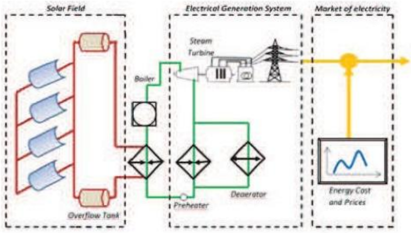

Fig. 2. Solar Thermal Plant with oversized oil overflow tank and oil-steam thermal exchange.

III. IMPLEMENTATION COSTS AND MANAGEMENT ANALYSIS

This comparative study uses one standard solar thermal plant with 50MW net output. 76 loops of solar collectors plus 12 modules in each loop are necessary for such plant. The average surface needed for this plant is 450.000m^2, considering high efficiency solar collectors and 200% solar multiple to obtain more production in low radiance periods. Real solar radiation values are going to be used to obtain numerical results, considering one general location with 37º latitude as it is usual for this kind of plant.

For the power block we consider 37% average conversion efficiency, 391ºC inlet temperature, 293ºC outlet temperature, 100bar boiler operating pressure and 20% of thermal power fraction for standby or startup.

The double-tank direct system (for seven hours of equivalent full load thermal energy) is performed with 20000m^3 storage volume, 36m diameter, 20m tank height and 391ºC fluid temperature [6], [7].

With these conditions the evaluation of the implementation costs has the numerical results shown in Table I.

TABLE 1. NUMERICAL RESUME FOR THREE STORAGE OPERATIONS IN SOLAR THERMAL PLANT: DOUBLE-TANK DIRECT SYSTEM WITH SEVEN HOURS OF EQUIVALENT FULL LOAD THERMAL ENERGY, DIRECT PRODUCTION OF ELECTRICITY WITHOUT STORAGE AND OVERSIZE IN TWO HOURS OF EQUIVALENT FULL LOAD THERMAL ENERGY OF OVERLOAD FLUID TANKS.

Cost Concept	7h TES	0h TES	2h equiv. TES
Site	6,004,789€	6,004,789€	6,004,789€
Solar Field	105,084,000€	105,084.000€	105,084,000€
Power Plant	35,420,000€	35,420,000€	35,420,000€
HTF System	15,011,990€	15,011,990€	15,011,990€
Thermal Storage	49,986,720€	0€	14,281,960€
Fossil Backup	16,250€	25,700€	19,250€
Contingency	21,150,920€	16,152,220€	17,580,430€
Indirect Cost	57,467,060€	43,885,660€	47,766,040€
O & M	33,573,540€	32,970,840€	33,465,530€
Ins. and Prop.	15,932,630€	12,167,190€	13,243,020€
Whole	**339,647,899€**	**266,722,389€**	**287,887,009€**

IV. MATHEMATICAL MODELS AND OPTIMIZATION.

We will optimize the concentrating solar generation system with thermal storage by a short term planning to less use non-linear functions and temporal variables. We will have a daily horizon of variation with discrete time variables.

Direct normal irradiation, which affects parabolic trough collectors, is related to the power supplied to the storage system and the power block, given by the following expression:

$$P_{Solar}(j) = P_{DNI}(j) \cdot A_{SolarField} \cdot F_{SolarMultiple} \quad (1)$$

Equation (2) gives the generation balance and costs of the solar plant operation, considering the efficiency and price factors in each step of the process. $P_{fadeout}(j)$ is the power reduction through defocus of collectors. Due to oversize of the solar field, sometimes it is not possible to evacuate the thermal energy obtained. P_{Warm} is the thermal power needed for the normal operation for the plant, and $P_{StartUp}$ is the thermal power necessary to run up the plant. In this equation the limits of thermal energy stored are shown in specific time units related to the amount of energy collected from the solar panels. The storage process is made up of the amount of thermal energy stored in tanks plus the amount of energy extracted from them. The subsequent efficiency factors are applied [8], [9]:

$$\begin{aligned} P_T = P_{solar}(j) + \frac{P_{Gas}(j)}{\eta_{Gas}} + P_A^+(j)\eta_{sto} - P_A^-(j) \\ - P_{fadeout}(j) - P_{StartUp}(j) - P_{Warm}(j) \qquad \forall j \in J \end{aligned} \quad (2)$$

The relationship between the energy stored in the synthetic oil tank (or molten salt tanks) and the power flow from collectors or towards the generation turbine can be expressed as (3):

$$E_A(j) = E_A(j-1) - \frac{P_A^+(j)}{\eta^+} + \eta^- P_A^-(j) - \Delta P_A^{loss} \ \forall j \in J \quad (3)$$

The benefit of gross power production for each hour is given in (4) where the corresponding expressions of transmission loses and self-consume costs have been considered for the final benefit, valued according to the current market energy prices.

$$\begin{aligned} (\Pi_{DM}(j) + \Delta\Pi)P_T(j) - (C_G P_{Gas}(j)) \\ - k_{grad}\Delta P_T^{Abs}(j) - \Pi_{DM}(j)P_{Grid}(j) \end{aligned} \quad (4)$$

The enouncement of the problem (Thermal Group Hourly Programming, TGHP) will be done by benefits optimization according to market power prices. Different operation regimes and thermal plant storage have been considered as mentioned in section IV. We will consider one-hour time intervals for Δj to construct the target function shown in (5) [10], [16], [17].

Target Function:

$$\sum_{j \in J} \left[(\Pi_{DM}(j) + \Delta\Pi)P_T(j) - (C_G P_{Gas}(j)) - k_{grad}\Delta P_T^{Abs}(j) - \Pi_{DM}(j)P_{Grid}(j) \right] \quad (5)$$

Structural and operational restrictions:

$$E_A(j) \le N_{AMax} \cdot \left(\frac{P_{Tdesign}}{\eta_{Tdesign}} \right) \quad (6)$$

$$E_{GasTotal} \le k \cdot \sum_j \frac{P_T(j)}{\eta_{Tdesign}} \quad (7)$$

Equation (6) shows the limitation of thermal storage with Plant Nominal Power. Equation (7) shows the limitation of Auxiliary Gas generation given by market conditions. Coefficient k can be 12% for Regulated Market or 15% for Free Market [11]-[13]. A fraction of this auxiliary energy source sometimes is required to start the power block, estimated in 36.5 MWht for a 50MW solar thermal plant [15].

Other variables and expressions can be obtained by deduction from these variables and equations.

V. RESULTS AND REMARKS

After programming these models, analyze their structuring and economical parameters we can observe (Table II) the energy production and cash-flow due to the use of different storage systems. We consider 30 years as the operation useful life for the plant [6].

TABLE II. NUMERICAL RESULTS FOR TREE OPTIONS OF THERMAL MANAGEMENT: DOUBLE DIRECT TANK, DIRECT PRODUCTION OF ELECTRICITY WITHOUT STORAGE AND INCREASED OVERFLOW TANK.

CSP plant with 7h TES	
Energy (kWh)	3,668,325,059.10
Energy Value	1,014,611,132.93€
After Tax Cash-flow	610,828,986.80€
CSP plant without thermal Storage	
Energy (kWh)	2,884,336,332.30
Energy Value	797,770,019.50€
After Tax Cash-flow	462,665,940.56€
CSP plant with greater overflow tanks	
Energy (kWh)	3,527,827,138.20
Energy Value	975,751,230.21€
After Tax Cash-flow	573,611,437.39€

To conclude, the models described in this work are not mutually exclusive; rather they can be applied in different economical situations and varied locations. The management of thermal storage is not necessary in power markets with regulated prices and enough solar resources [11], [14]. In this case, it is better to generate power according to the thermal resource available. For plants with lower solar resources and free market operation the use of double-tank storage systems is necessary. This allows adaptation of production to higher price periods. In double direct storage systems the energy production is not enough to justify the solutions in which higher storage than 7 equivalent hours is needed.

Finally, for higher solar resource plants and average production over 15 hours/per day intermediate storage systems are more profitable with lower investment costs, thus producing power with a higher efficiency and less capacity.

VI. APPENDIX: LIST OF SYMBOLS

$P_{DNI}(j)$	Direct Normal Radiation as solar resource (MWt/m2)
$A_{SolarField}$	Real Collection surface for 50MW solar thermal plant
$F_{SolarMultiple}$	Oversize of solar collection surface (%)
$P_{Solar}(j)$	Power (MWt) received from the solar concentrators in the hour j as known value
$P_{Tdesign}$	Nominal Power in Steam turbine (MW)
$P_T(j)$	Electrical power generated in period j (MW)
$P_{fadeout}(j)$	Reduction of radiation by fade out of solar collectors when production peaks occur (MWt)
P_{Warm}	Thermal power needed for the normal operation for the plant (MWt)
$P_{StartUp}$	Thermal power necessary to run up the plant (MWt)
$P_A^+(j), P_A^-(j)$	Thermal energy interchanges in period j (MWt).
N_{AMax}	Maximum stored energy in thermal tanks (equivalent hours of full load production)
$P_{Gas}(j)$	Electricity generated by external gas combustion in period j (MWt)
η_{sto}	Storage efficiency (%)
η_{Gas}	Efficiency of thermal generation by auxiliary gas source (%)
$E_{GasTotal}$	Legal maximum energy generated by gas (MWh)
$\Pi_{DM}(j)$	Real time sold energy price in period j (€/MWh)
$\Delta\Pi$	Premium (€/MWh)
C_G	Cost of gas considering free market prices (€/MWh)

ACKNOWLEDGMENT

Thanks are due to Julio Usaola and Edgardo D. Castronuovo from the Electric Engineering Department of Universidad Carlos III de Madrid for useful discussions.

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ARTÍCULO 2

WORLD LOCATION AS ASSOCIATED FACTOR FOR OPTIMAL OPERATION MODEL OF PARABOLIC TROUGH CONCENTRATING SOLAR THERMAL POWER PLANTS

In Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016; IEEE: Florence, Italy, 2016; 1–6. DOI: 10.1109/EEEIC.2016.7555718.

Abstract

Concentrating Solar Thermal Power (CSP) technology provides a competitive source of energy for electricity generation. Within this technology and thanks to its great potential, Cylindrical Parabolic Concentrators (CCP) plants have become the type of electricity generation by renewable solar energy most widely spread around the world. Nonetheless, the plant design and operation model are not unique; they must be adapted to the parameters of solar radiation from each particular location.

This work focuses on the search of a mathematical model of CCP for optimal operation options, of double tank molten salt Thermal Energy Storage (TES) size and plant operation, designed for four different world locations. For each world location and within a regulated electric scenario, the analysis of the different ways of operation provides meaningful insights into the electricity generated.

Therefore, the plant deployment points of storage tanks size and electric power generation can be established for optimal operation according to each radiation area. This comparative study uses a CCP standard solar thermal plant with 2 blocks of $50MW_e$ net output. Certain parameters have been preset on modelling environment in order to establish a common basis for the model comparisons.

Resumen

La tecnología solar térmica de concentración (CSP) proporciona una fuente competitiva de energía para la generación de electricidad. Dentro de esta tecnología y gracias a su gran potencial, las plantas de concentradores cilindro parabólicos (CCP) se han convertido en el tipo de generación de electricidad por energía solar renovable más extendida por todo el mundo. Sin embargo, el diseño de la planta y el modelo de operación no son únicos; deben adaptarse a los parámetros de radiación solar de cada lugar en particular.

Este trabajo se centra en la búsqueda de un modelo matemático de CCP para operaciones óptimas de generación, con almacenamiento térmico mediante doble tanque de sales fundidas, diseñado para cuatro ubicaciones diferentes alrededor de mundo. Para cada ubicación y dentro de un escenario eléctrico regulado, el análisis de las diferentes formas de operación proporciona información significativa sobre la electricidad generada.

Por lo tanto, los puntos de implantación de la planta de generación de energía eléctrica se pueden establecer para un funcionamiento óptimo de acuerdo con cada área de radiación. Este estudio comparativo utiliza una planta termosolar estándar con tecnología de colectores cilindro parabólicos con 2 bloques de salida neta de $50MW_e$. Ciertos parámetros se han predefinido en el entorno de modelado con el fin de establecer una base común para las comparaciones de modelos.

2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)

7-10 June 2016, Florence, Italy

Conference Proceedings

CD-ROM CFP1651I-CDR ISBN 978-1-5090-2319-6

World location as associated factor for optimal operation model of Parabolic Trough Concentrating Solar Thermal Power Plants

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***Abstract*—**Concentrating Solar Thermal Power (CSP) technology provides a competitive source of energy for electricity generation. Within this technology and thanks to its great potential, Cylindrical Parabolic Concentrators (CCP) plants have become the type of electricity generation by renewable solar energy most widely spread around the world [1]. Nonetheless, the plant design and operation model are not unique; they must be adapted to the parameters of solar radiation from each particular location. This work focuses on the search of a mathematical model of CCP for optimal operation options, of double tank molten salt Thermal Energy Storage (TES) size and plant operation, designed for four different world locations. For each world location and within a regulated electric scenario, the analysis of the different ways of operation provides meaningful insights into the electricity generated. Therefore, the plant deployment points of storage tanks size and electric power generation can be established for optimal operation according to each radiation area. This comparative study uses a CCP standard solar thermal plant with 2 blocks of $50MW_e$ net output. Certain parameters have been preset on modelling environment in order to establish a common basis for the model comparisons.

Keywords—Solar thermal, CCP, World location, Molten salt TES, Operation model

I. INTRODUCTION

International laws, such as European Directive 2001/77/EC (Promotion of electricity generated from renewable energy in inner electricity market) [2], and U.S. Public Law 109–58 (Energy policy act of 2005) [3], focus their efforts on promoting the development and use of renewable energy, and more specifically in the implementation of solar thermal energy for electric energy generation. Such is the Spanish case, where the implementation of solar thermal technologies is prioritized for optimizing the energy mix choice from renewable sources [4].

Solar reception technology has developed new models and architectures able to obtain the best amount of energy from the sun in smaller surfaces each time. The research lines of Modelling of steam based Paraboloidal Dish concentrators [5], Optical Efficiency of Low concentrating solar energy [6] and SunSpear calibration for monitoring in solar concentrators [7] let us to define the reception systems adapted to specific plant requirements and the economical restrictions of the market of electricity. However, Concentrating Solar Power (CSP) systems, and specifically Cylindrical Parabolic Concentrators (CCP) [1], have been the most implemented renewable energy resources for the last ten years [8].

The development of thermal storage systems lets the projection of CCP plants increase in order to generate electricity in partial cover moments and even after the sunset, being able to meet the requirements of electricity energy consumption.

Nowadays, the generation of electricity by renewable resources from solar energy and its integration into the electrical market depend on solar availability, regardless of the plant location. The selection of parameters and specific variables such as storage capacity, reception surface or generation systems, lead us to propose some specific optimization enouncements, and what is the object of this article, to obtain high efficiency proposals for optimal operation according to each place. Thus, four geographic locations have been selected for this work, between the 26th and 37th latitudes of both, Northern and Southern hemispheres, to be considered representative places where the CCP plants are likely to be installed. The specific locations used for this work are: Vittoria (Italy), Cairo (Egypt), Meekatharra (Australia), Atacama Desert (Chile).

A regulated electric prices scenario and non-economical analysis have been considered for the implemented simulation model in this work.

II. CCP OPERATION PERFORMANCES

A. DNI and location

The functional components of a standard thermal solar plant by CCP are considered hereafter for their latter modelling and study. In this modelling work, location provides the sum of Direct Normal Irradiance (DNI) per square meter evaluated in a yearly period. This location would be considered as a factor for the design of the plant, as a direct influence over total surface, total equivalent storage and final production of electricity. Henceforth, we are going to present

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the most frequent classification of solar radiation surfaces around the world, considering four intervals for the study. These intervals correspond to four viable options in the implementation of a system of thermal generation.

The first one considers 5KWh/m^2 of solar irradiation as total radiation on a specific location, obtaining the equivalent 1800KWh/m^2 per year. The second one considers 6 KWh/m^2 for daily solar radiation with 2200 KWh/m^2 as radiation per year. Third one considers 7 KWh/m^2 for daily solar radiation with 2550 KWh/m^2 as radiation per year. Finally, the last one considers 8 KWh/m^2 for daily solar radiation with 2900 KWh/m^2 as radiation per year.

B. Solar field as reception system

Solar reception in CSP is mainly performed in infrared spectrum. The thermal exploitation by active transmission fluid (HTF) in medium temperature (from 200ºC to 600ºC), and concentration by CTS (Concentrating Thermo Solar Systems) include a large array of technological families, which can be categorized according to the way they focus the sun rays as well as the technology used to receive solar energy [5].

Parabolic troughs (line focus, mobile receiver), consist of parallel rows of mirrors (reflectors) curved in one dimension to focus sunrays. The mirror arrays can be more than 100m long with the curved surface 5m to 6m across. Stainless steel pipes (absorber tubes as heat collectors) have a selective coating that is designed to allow pipes to absorb high levels of solar radiation while emitting very little infra-red radiation. The pipes are isolated by an evacuated glass envelope. Both the reflectors and the absorber tubes move following the sun with one degree of freedom (North-South axes). This is the most usual solution for medium investment cost, which is the reason why this is the main technology used in our model to optimize the production of electricity with Thermal Energy Storage (TES).

Solar Multiple (SM) values greater than 1 are necessary to ensure the technical feasibility of the plant during periods of low solar radiation, or during times of partial coverage of the solar field. Similarly, for energy storage in molten salt tanks it is necessary to oversize the solar field providing surplus of thermal energy. In this work, a standard SM value of 1.7 has been preset in the mathematical model for the four areas of classification. The plant model comparison attends to the only factor of thermal storage in the molten salt tanks as it can be seen in point 2.3.

C. Thermal storage management

Two possible configurations are found in these power systems depending on the management of the thermal energy obtained from the solar field before it is used by the power block [6].

The first one is to consider direct generation without TES. In this case all the thermal energy obtained from the solar field is directly driven to the power block and then used to generate electricity. When the solar resource produces overheating in the solar field, the only solution is the partial fadeout of collectors that defocuses them and so reduces the solar collection. This option is more frequent when the solar resource along the yearly period is enough to produce electricity during fifteen or more hours per day as average. The schema in Fig. 1 [9] shows a CCP plant with direct dispatching and oil-steam thermal exchange.

The second one is to consider the use of a double tank molten salt as TES into the CCP plant, as shown in Fig. 2 [9]. The Double Tank Direct System (thermal exchange between two tanks HT/LT with the same HTF) lets to divert excess heat to a thermal storage material during the day. When production is required after sunset, the stored heat is released into the steam cycle and the plant continues producing electricity. Sodium and potassium molten salt is currently one of the most efficient thermal storage materials in medium temperature concentration solar thermal plants. Molten salt mechanical and chemical stability reduces storage cost above 65% at the same time that it increases thermal reversibility related to other thermal storage systems [10].

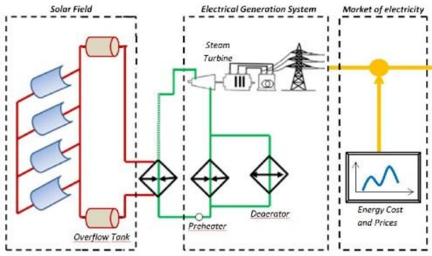

Fig. 4. Parabolic Trough plant with direct dispatching and oil-steam thermal exchange [9].

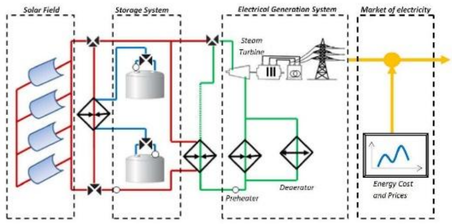

Fig. 5. Parabolic Trough plant with double tank TES system and oil-salt-steam thermal exchange [9].

The double-tank direct system increases the complexity of installation and therefore its implementation costs. The whole efficiency of this double-thermal exchange system (synthetic oil in the solar field, molten salt in storage and steam in the power block) is lower than the single-thermal exchange system (synthetic oil in the solar field and steam in the power block). Nevertheless, the double-tank system is a frequent solution either when the solar resource is not enough to obtain the average production of fifteen hours per day in one yearly period, or when the production of electricity needs adaptation to the free market electricity prices (without prices regulation or pool distribution).

The high efficiency of the heat exchange with water allows the use of these salts to transport solar heat to produce water steam. The expansion of the steam in conventional turbines makes the electricity production available. The solidification point of these salts makes them less useful in solar fields and pipes, making the synthetic oil the most common resource.

D. *Plant implementation basics*

This comparative study starts at one standard solar thermal plant with 2 block of CCP $50MW_e$ net output. Considering a Solar Multiple equal to 1 (SM=1), 156 loops of solar collectors plus 24 modules in each loop are necessary for such plant. The average surface needed for this plant is 434.318 m^2. According to the different location considered, real solar radiation values are used to obtain numerical results. For the power block we consider 37% average conversion efficiency, 391°C inlet temperature, 293°C outlet temperature and 20% of thermal power fraction for standby or start-up. Data from the double-tank direct system (for seven hours of equivalent full load TES) are: $20000m^3$ storage volume, 36m diameter, 20m tank height and 391°C fluid temperature [11, 12]. Table 1 shows a summary table that listed the different variables to be analyzed (such as their scope) for each specific location.

TABLE I. CCP PLANT PERFORMANCE SUMMARY

Performance summary	
Location	Vittoria (Italy) Cairo (Egypt) Meekatharra (Australia) Atacama Desert (Chile)
Plant management	Direct generation without thermal storage Double tank molten salt thermal storage
Solar multiple	SM=1.7

III. PLANT MODELLING AND SIMULATION PROCESS

Concentrating solar generation system with TES is optimized by a short term planning to less use of non-linear functions and temporal variables. In the same way, a daily horizon of variation with discrete time variables is set.

DNI, which affects parabolic trough collectors, is related to the power supplied to the storage system and the power block, given by the following expression:

$$P_{Solar}(j) = P_{DNI}(j) \cdot A_{SolarField} \cdot F_{SolarMultiple} \quad (1)$$

Equation (2) gives the generation balance of the solar plant operation, considering the efficiency factors in each step of the process. $P_{fadeout}(j)$ is the power reduction through defocus of collectors. Due to oversize of the solar field, sometimes it is not possible to evacuate the thermal energy obtained. P_{Warm} is the thermal power needed for the normal operation for the plant. $P_{StartUp}$ is the thermal power necessary to run up the plant. In this equation the limits of thermal energy stored are shown in specific time units related to the amount of energy collected from the solar panels. The storage process is made up of the amount of thermal energy stored in tanks plus the amount of energy extracted from them.

The subsequent efficiency factors are applied [13, 14]:

$$\begin{aligned} P_T &= P_{solar}(j) + P_{Gas}(j) + P_A^+(j)\eta_{sto} - P_A^-(j) \\ &- P_{fadeout}(j) - P_{StartUp}(j) - P_{Warm}(j) \quad \forall j \in J \end{aligned} \quad (2)$$

The relationship between the energy stored in the synthetic oil (molten salt) tanks and the power flow from collectors or towards the generation turbine can be expressed as (3):

$$E_A(j) = E_A(j-1) - \frac{P_A^+(j)}{\eta^+} + \eta^- P_A^-(j) - \Delta P_A^{loss} \ \forall j \in J \quad (3)$$

An auxiliary energy source is required to start the power block, usually from a gas boiler system and estimated in 36.5 MW_{th} for a $50MW_e$ CCP plant [15].

Structural and operational restrictions:

$$E_A(j) \leq N_{AMax} \cdot \left(\frac{P_{Tdesign}}{\eta_{Tdesign}} \right) \quad (4)$$

In this work, the sunshine and cloudy periods along the year are also considered for the four representative locations around the world: Vittoria (Italy), 36°57'N, 14°31'E; Cairo (Egypt), 30°2'N, 31°18'E; Meekatharra (Australia) 26°35'S, 118°30'E; Atacama Desert (Chile), 27°5'S 69°10'W. The average daily sum of solar direct irradiation for each specific place is shown in Table 2.

TABLE II. AVERAGE DAILY SUM OF SOLAR DIRECT IRRADIATION

Location	**Coordinates**	**Daily solar direct irradiation**
Vittoria	36°57'N, 14°31'E	5 KWh/m^2
Cairo	30°20'N, 31°18'E	6 KWh/m^2
Meekatharra	26°35'S, 118°30'E	7 KWh/m^2
Atacama Desert	27°50'S, 69°10'W	8 KWh/m^2

The optimization is done one year at a time. For the specific formulation, we are going to consider the real solar radiation in hourly distribution for the year 2014 [16, 17].

Finally, the electrical power installed at any of the four locations is limited to $100MW_e$; defining similar conditions of turbine and power block in each configuration, allowing the comparison of results and optimizations.

A. *Simulation process*

Simulations are made according to each singular location and its average daily sum of solar direct irradiation. The simulation process focuses on the one hand in the direct generation without energy storage, and on the other hand in an environment with double tank molten salt.

Molten salt tanks TES capacity is measured in equivalent hours of full load capacity of the plant at SM=1. Considering direct dispatching as starting point for the simulations, double tank capacity is considered between zero and seven hours of equivalent TES. Table 3 shows both simulation scenarios as well as the study range of the variables established. Fig. 3 plots the simulation environment carried out to obtain the electrical power generated and the TES for each singular case.

TABLE III. SCENARIOS OF SIMULATION PER 50 MW POWER BLOCK

Scenario	Variables			
	Net output (MWh_e)	*Power block thermal demand (MW_{th})*	*SM value*	*Storage range (equivalent hours)*
Direct generation	50	143.75	1.7	[0]
Double tank molten salt thermal storage	50	143.75	1.7	[1;1;7]

IV. RESULTS AND REMARKS

Our first basic analysis considers the net annual energy inlet to the double tank molten salt. This value is given by the annual sum of the parabolic trough collectors' energy surplus, sent into the molten salt storage tanks, when solar radiation is enough to supply the power block thermal needs. The solution of the optimization model introduced gives the storage values depending on tanks capacity and operation strategy.

Fig. 4 plots the net annual double tank thermal energy into storage as a function of TES. Data represent the optimal solution for the energy dynamics of storage and generation modes in hourly distribution for the four locations. As shown in Table 3, results are referred to a 2 blocks of MW_e standard CCP plant, considering a fix solar multiple of 1.7, and thermal storage between ranges and interval [0;1;7]. Fig. 4 shows clearly the optimum TES size for each location. This value is determined by the size of the storage tank that maximizes the thermal energy delivered by the solar field to store.

For location 1 (Vittoria), optimum TES is set in 3 hours, with an amount of thermal energy sent to storage of 95.20 GWh_{th}. TES=5 is the biggest size storage for location 2 (Cairo), with an annual thermal energy into store of 163.91 GWh_{th}.

Regarding location 3 (Meckatharra), 184.49 GWh_{th} is the energy that maximizes the storage capacity, which corresponds to TES=5 like Cairo. Atacama Desert, corresponding to location 3, reaches a thermal energy sent into storage of 237.89 GWh_{th} for TES=6. Finally, for SM=1.7 used as design parameter in this work, no place of the locations under study reaches the maximum TES analyzed of 7 equivalent hours.

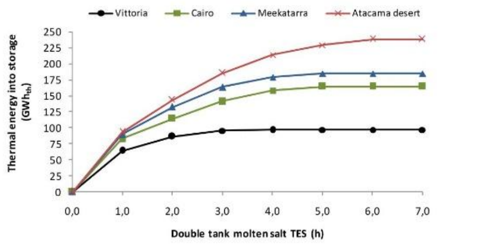

Fig. 4. Annual double tank thermal energy into storage as a function of TES.

Data from Fig. 4 focus on the amount of net annual thermal energy recess in storage tanks. However, it does not take into account the minimum energy that must remain continuously stored into tanks to maintain the operation temperature of the molten salt. Molten salt lower limit temperature is configured to 220°C by its thermal stability [18]. This factor significantly limits the amount of stored thermal energy available to be delivered to the power block, thereby affecting the electricity generated. As a function of TES, our second analysis focuses on the relationship between the annual electric power production in the grid coupling and net annual energy inlet to the double tank molten salt previously introduced.

In Fig. 5, 6, 7 and 8, the optimization model shows, for each area of radiation considered, the points that define the strategy of energy storage and electric power generated, adjusted to the lowest molten salt tanks investment and the highest production.

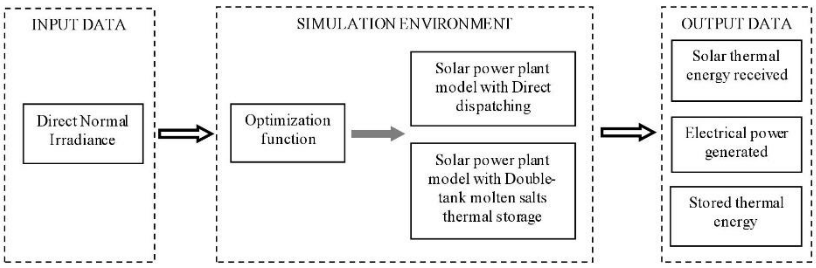

Fig. 3. Operation model simulation environment.

Location 1 (Vittoria) is represented in Fig. 5. According to the production of electricity, this figure shows that the optimal point in the CCP plant is located on 3 hours of equivalent thermal storage, as for thermal energy into storage factor. With solar multiple of 1.7 and a production of 189.78 GWh_e, the result showed in this figure means that a higher storage does not imply greater total annual production. So, an increase of the storage tanks capacity would increase the manufacturing investment of the plant without any real benefit obtained by the production of energy.

Location 2 (Cairo) is represented in Fig. 6. The figure shows that the optimal TES according to the thermal energy into tanks is set in 5 equivalent hours. Nevertheless, the optimal electric production (292.16 GWh_e) is placed on the equivalent TES of 4 hours. It is also plotted that a larger storage does not imply a greater total annual production. Therefore, although increasing the amount of thermal energy input to the tanks to TES=5, this energy is not delivered to the power block but rather is kept in order to maintain the molten salt operating temperature. Thus, the optimum operating point and TES size of the plant for this location is TES=4.

Fig. 7 corresponds to location 3 (Meekatharra). Although the thermal energy into tanks increases to TES=5, in this figure it is observed that the molten tank oversize higher than TES=4 does not improve the production of electrical energy. The justification for this case coincides with the one from location 2 (Cairo). So, the point of optimum production with less investment corresponds to the plant with 4 hours of equivalent TES and an electric production of 299.85 GWh_e.

Location 4 (Atacama Desert) is represented in Fig. 8. The point of optimum electricity production (331.84 GWh_e) with lower plant investment corresponds to 5 hours of equivalent thermal storage. However, according to the energy into storage, 6 hours is the most appropriate TES size. Similar to Cairo and Meekatharra, for this location increasing the power input to the tanks it is not reflected in electricity production due to minimal thermal storage requirements.

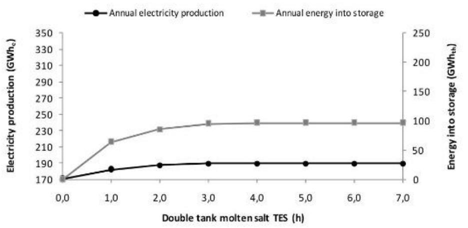

Fig. 5. Annual net electricity production and thermal energy into tanks storage as a function of TES. Vittoria.

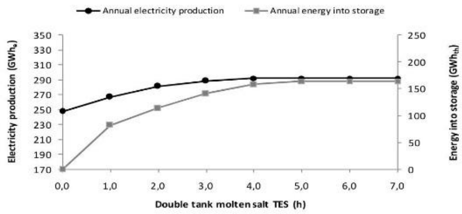

Fig. 6. Annual net electricity production and thermal energy into tanks storage as a function of TES. Cairo.

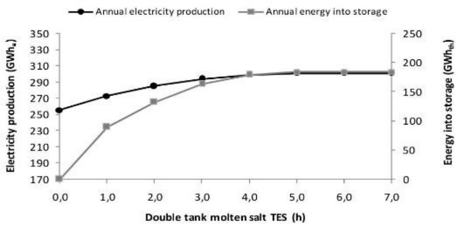

Fig. 7. Annual net electricity production and thermal energy into tanks storage as a function of TES. Meekatharra.

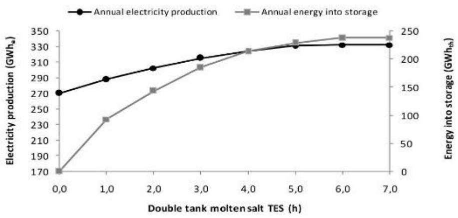

Fig. 8. Annual net electricity production and thermal energy into tanks storage as a function of TES. Atacama Desert.

Table 4 shows the comparative recap of optimum TES according to net electric generation and net thermal energy from the solar field into storage.

TABLE IV. OPTIMAL OPERATION PLANT TES RECAP FOR SM=1.7

Location	Daily DNI (KWh/m^2)	Optimal TES according to net electric generation (h)	Optimal TES according to net thermal energy into storage (h)
Vittoria	5	3	3
Cairo	6	4	5
Meekatharra	7	4	5
Atacama Desert	8	5	6

V. Conclusions

In this work a standard CCP plant of 2 blocks of 50MW$_e$ has been analyzed from an operation point of view. Electric power has been generated according to the thermal resource available. The management of thermal storage according to electricity market is not necessary in power markets with regulated prices and enough solar resources [17, 19]. Four locations representing different solar direct irradiation areas have been studied. Solar multiple value has been fixed to 1.7 in the simulation environment. The optimization of the operation model has been carried out according to the size of the thermal energy storage in a double tank molten salt, and represented by its equivalent TES measured in hours.

The first scenario considered in this paper corresponds to direct generation plant without thermal storage. For location 1 (Vittoria), electricity production increment between the plant without storage and TES values that maximizes energy delivery to the power block is 19.03 GWh$_e$. Within a weak incidence, the energy production is not enough to justify the investment plant solutions with double tank molten salt storage system. For the other locations, a significant electric energy generation increment can be observed between plant with and without storage. The generation differentials are 43.98 GWh$_e$, 45.12 GWh$_e$ and 62.27 GWh$_e$ for Cairo, Meekatharra and Atacama Desert respectively.

The second scenario analyzes the net thermal energy sent into storage tanks and net electric energy produced by the plant, according to the different values of TES. As seen in Table 4, the limiting factor for optimal TES is the net electricity production. Thus, for optimal CCP plant implementation and operation, no matter where the CCP plant is located, the size of the salt tanks should be sized taking into account the electricity generated and not the energy into storage system from the solar field. This implementation has been influenced, as already indicated, by the internal thermal energy consumption of the storage system to maintain the temperature of molten salt over the minimum operation point.

List of Symbols

$P_{DNI}(j)$	Direct Normal Irradiance as solar resource (MW$_{th}$/m^2)
$A_{SolarField}$	Real Collection surface for 50MW$_e$ solar thermal plant
$F_{SolarMultiple}$	Oversize of solar collection surface (%)
$P_{Solar}(j)$	Power (MW$_{th}$) received from the solar concentrators in the hour j as known value
$P_{Tdesign}$	Nominal Power in Steam turbine (MW$_e$)
$P_T(j)$	Electrical power generated in period j (MW$_e$)
$P_{fadeout}(j)$	Reduction of radiation by fade out of solar collectors when production peaks occur (MW$_{th}$)
P_{Warm}	Thermal capacity needed for the normal operation for the plant (MW$_{th}$)
$P_{StartUp}$	Thermal capacity necessary to run up the plant (MW$_{th}$)
$P_A^+(j), P_A^-(j)$	Thermal capacity interchanges in period j (MW$_{th}$).
N_{AMax}	Maximum stored energy in thermal tanks (equivalent hours of full load production)
$P_{Gas}(j)$	Electricity generated by external gas combustion in period j (MW$_e$)
η_{sto}	Storage efficiency (%)
η	Efficiency (%)
E_A	Stored energy in thermal tanks (equivalent hours of full load production).

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ARTÍCULO 3

REGULATION ISSUES FOR RENEWABLE ENERGY INTEGRATION INTO ELECTRICAL MARKETS

In Proceedings of the IEEE 17th International Conference on Environment and Electrical Engineering (EEEIC), Milan, Italy, 6-9 June 2017; IEEE: Milan, Italy, 2017; 1-6. DOI: 10.1109/EEEIC.2017.7977528.

Abstract

European legislation evolution has followed the dynamics of deregulation that allowed the evolvement of the installed power capacity on renewable resources in parallel with the development of the technologies on renewable resources. This depends directly on technical and legislative factors related to the economic support to the investment for the construction of this type of power generation systems. The strengths and weaknesses of each stage of regulation can be analyzed following the Spanish energy model.

The first phase of liberalization of the market for the production of electric power has been funded. Here technologies used for the generation of installed power from renewable sources have not observed criteria of availability of renewable resources and efficiency in electricity production, as much as expected. The demand for electric energy should match efficient generation, as peaks of consumption demand higher production of electricity. Thus, there should be no need to have installed total power several times greater than the electrical power required.

The evolution of electric generation systems according to relevant legislation demonstrates that optimizing the choice of energy mix from renewable sources must prioritize the implementation of concentrating solar thermal plants.

Resumen

La evolución de la legislación europea ha seguido la dinámica de desregulación que ha permitido la evolución de la capacidad de producir energía procedente de recursos renovables en paralelo con el desarrollo de las tecnologías basadas en dichos recursos renovables. Esto depende directamente de factores técnicos y legislativos relacionados con el apoyo económico a la inversión para la construcción de este tipo de sistemas de generación de energía. Las fortalezas y debilidades de cada etapa de la regulación se pueden analizar siguiendo la el modelo energético español.

Se ha financiado la primera fase de liberalización del mercado de la producción de energía eléctrica. Aquí las tecnologías utilizadas para la generación de energía instalada a partir de fuentes renovables no han observado los criterios de disponibilidad esperados de recursos renovables y eficiencia en la producción de electricidad. La demanda de energía eléctrica debe coincidir con la generación eficiente, ya que los picos de consumo exigen una mayor producción de electricidad. Por lo tanto, no debería haber necesidad de haber instalado una potencia total varias veces mayor que la potencia eléctrica requerida.

La evolución de los sistemas de generación eléctrica de acuerdo con la legislación pertinente demuestra que la optimización de la elección del mix energético a partir de fuentes renovables debe priorizar la implementación de plantas termosolares concentradoras.

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Regulation issues for renewable energy integration into electrical markets

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***Abstract*—**European legislation evolution has followed the dynamics of deregulation that allowed the evolvement of the installed power capacity on renewable resources in parallel with the development of the technologies on renewable resources. This depends directly on technical and legislative factors related to the economic support to the investment for the construction of this type of power generation systems. The strengths and weaknesses of each stage of regulation can be analyzed following the Spanish energy model. The first phase of liberalization of the market for the production of electric power has been funded. Here technologies used for the generation of installed power from renewable sources have not observed criteria of availability of renewable resources and efficiency in electricity production, as much as expected. The demand for electric energy should match efficient generation, as peaks of consumption demand higher production of electricity. Thus, there should be no need to have installed total power several times greater than the electrical power required. The evolution of electric generation systems according to relevant legislation demonstrates that optimizing the choice of energy mix from renewable sources must prioritize the implementation of concentrating solar thermal plants.

Keywords*— *Operation model, integration of renewable energy, regulation of electricity, electricity market

I. INTRODUCTION

Throughout the last two decades, the European directives have laid the basics of a support system to renewable resources. Nowadays, the European policy in this area is aimed at a phase of stabilization of resources and sustainability of the generation systems achieved, maintaining the objectives set for 2020.

The control of energy consumption in Europe and the increased use of energy from renewable sources, together with the energy savings and greater energy efficiency have been an important part of the package of measures to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change [1], and other commitments of international community. In addition, these factors have played an important role in promoting the security of energy supply, technological development and innovation. This provides opportunities for employment and regional development, especially in rural and isolated areas.

The directive 2001/77/EC [2] defined the different types of energy from renewable sources. The Directive 2003/54/EC [3] established definitions applicable to the electricity sector in general for the sake of legal certainty and clarity.

The Council of Europe (March 2007) reaffirmed the commitment of the Community with the development of energy from renewable sources (EU-wide) beyond 2010. It approved the mandatory target to reach a market share of 20% of energy proceeding from renewable sources in the entire consumption of EU energy in 2020.

Regarding production sustainability, different directives from 2009 [4] have established convenience that energy prices reflect their external costs, including those from production, consumption, environmental, social and health.

Throughout 2014 there have been significant changes onstage of geostrategic energy in Europe (European Council agreement on the framework for action in the field of climate and energy by 2030, electric markets link). Thus, the Member States and the Institutions must cooperate closely to develop common policies addressed at coordinating the different policies implemented by each country, in order to ensure consistency with their common objectives. In the international context, where competition is more valuable than cooperation, both Member States and EU institutions should take advantage of the economies of scale for a European joint action.

In the electricity sector, the objectives for the first half of the 21st century will require qualitative changes in the regulatory liberalized standard models toward an increased weight of regulation. These changes would require addressing the regulatory design process in a unified way. However, in the EU, where there is a common competition policy, energy regulatory fragmentation is remarkable [16].

That is the reason why public aid is needed to achieve the objectives of the Community, with a view to the expansion of electricity production from renewable energy sources. In particular, electricity prices in the national market reflect neither all costs nor the environmental and social benefits of the used renewable sources.

To ensure the achievement of the overall national mandatory targets, Member States have designed a progressive national plan of action on renewable energy,

978-1-5386-3917-7/17/$31.00 ©2017 IEEE

which would allow them to achieve their compulsory final targets. According to the EU directives mentioned, each Member State must evaluate their forecasts of gross energy final consumption, and establish the contribution that energy efficiency and energy saving make to their national targets. Member States must take into account the optimal combination of technologies and renewable resources to improve energy efficiency.

To analyze the achievement of the integration targets, a regulated/free market electric price scenario has been considered in a simulation model of generation dynamics in standard renewable system. The production results have been compared considering the changes of operation given by the changes of the electricity market.

In order to validate the results, some specific values from real renewable resources plants have been considered over the influence of Spanish electrical markets.

II. Renewable Energy Mix for Optimization of the Installed Power

Table 1 shows the classification of technologies and resources based on their capacity factor (*cf*) in Spain at the end of 2014 [17]. It is related to technologies leading towards a scenario of generation by using renewable resources. They have reached a total installed power several times higher than expected in Spain by the most optimistic estimations made several years ago.

TABLE I. CLASSIFICATION OF TECHNOLOGIES, RESOURCES AND THEIR *cf*

TECHNOLOGY	Installed Power (MW)	Generated Energy (GWh)	Capacity Factor (%)
Solar Thermal	2.496	4.853	71,90
Wind Power	22.949	55.767	61,73
PV Azimuth	4.711	8.258	85,57
Biomass	670	3.789	71,98
Hydroelectric	19.650	36.780	50,84
Biogas	223	907	50,84
Waste	276	595	26,95

The cf of a power plant is the ratio of its output over a period of time to its potential output if continuous operation over the same period of time was possible. The *cf* should not be confused with the availability factor of the power plant. It is defined as the amount of time that it is able to produce electricity over a certain period divided by the amount of the time in the period.

Fig. 1 and 2 below show the evolution of the renewable energy mix in Spain for the last two decades.

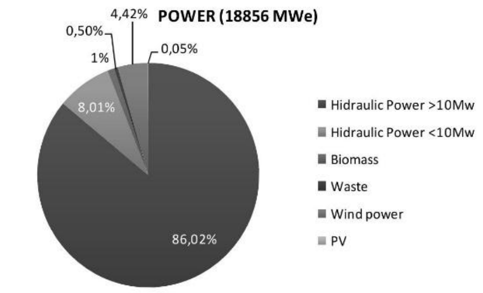

Fig.1a Evolution of renewable installed power (1998).

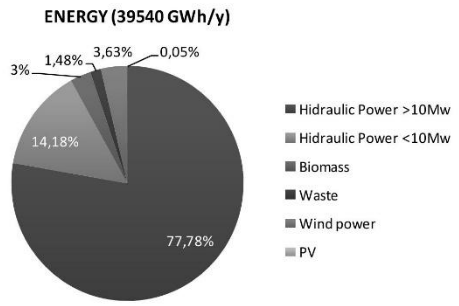

Fig. 1b. Evolution of renewable generated energy (1998).

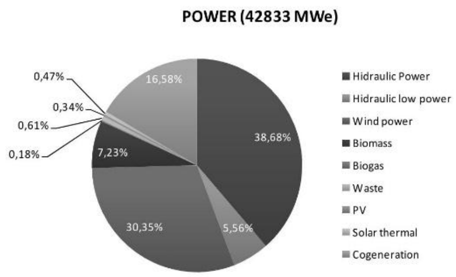

Fig. 2a. Evolution of renewable installed power (2014).

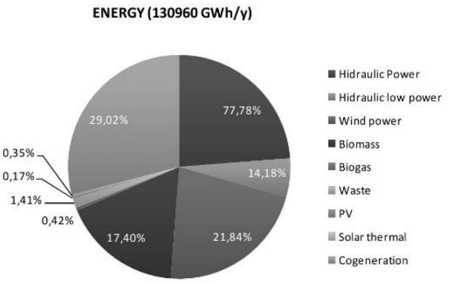

Fig. 2b. Evolution of renewable generated energy (2014).

This energy mix has been the product of the incentive of generation facilities without attention to their *cf*, by which the power of renewable energy installed must correspond with energy generation of equal magnitude. This production would provide a real answer to the requirements of energy demand of the national power grid.

Thus, starting from a roof of generation shown in Fig. 3, which marks the limits on the availability of renewable resources, the model of energy mix that is proposed in Fig. 4 corresponds to a balanced distribution between installed power, energy resource available, energy generated and real demand of the set of consumers connected to the network [14].

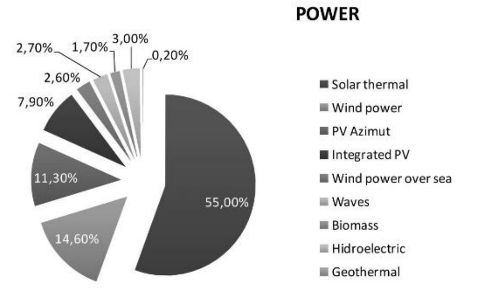

Fig. 3. Potential of generation for renewable resources [14].

Here it can be observed how the strengthening of solar plants concentration would increase the *cf* of the set of technologies through renewable resources to cover 55% of the installed power, as well as 100% of the electrical power demand.

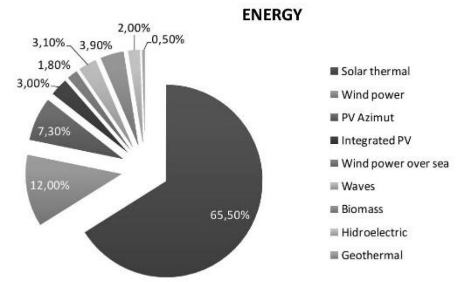

Fig. 4. Proposal for a technological mix (supply 100% of the total energy demand in Spain) [14].

III. Operation cost and feasibility of exploitation in non-regulated systems. The case of PT power plants

The requirement for competitive concurrency procedures for solar-only Parabolic Trough (PT) thermal power plants, as well as the promotion of these technologies in the market on an equal condition with the rest of technologies, come from EU guidelines and policies both to support the renewable energy and to protect the environment.

The incentives of this regulated market, until its disappearance, have been established through the market operator, with a base rate and lower and upper limits on this basis depending on the premiums.

In Fig. 5 the general structure of operation and players in the national electricity market is shown, including the participation of producers in regulated regime of remuneration (e.g. plants of concentrating thermal generation in high temperature) [12].

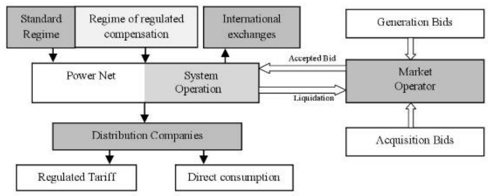

Fig. 5. Participation in the Spanish electricity market [12].

In this market system, the producers are entering the market for purchase and sale of energy with the same technical restrictions, although with sale priorities for the producers of energy from renewable resources established from the different rules of the market operator and the state legislation in this area.

For concentrating solar plants (CSP), other factors different from the market ones can be found that influence the operation and improvement of the economic viability of the plant. Both the use of storage technologies and oversizing of solar fields allow us to match the production of electricity and the solar resource available to the energy demand and the selling price.

Through a system of plant structural simulation [15] comparisons can be made in economic operation of plant and results in terms of constructive parameters, sizing, disposed auxiliary energy by gas boiler, and operation strategies.

In Fig. 6 a functional model of the PT plant and process of simulation used for this evaluation is shown.

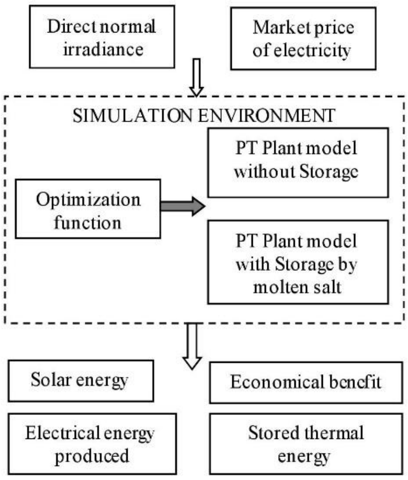

Fig. 6. Functional model for a PT Plants [15].

With this process of simulation, we can get a set of results of production and economic viability. These would be improved, by a proper campaign of incentives to production on renewable resources. Table 2 shows the results of electricity production for a real 50MWe PT power plant located in Spain.

TABLE 2. REAL ELECTRICITY PRODUCTION DATA FOR A PT POWER PLANT.

50MWe PT power plant	
Energy generated (GWhe)	3,668.32
Energy Value (Mio.€)	1,014.61
After Tax Cash-flow (Mio.€)	610.82

This analysis shows that the technology of thermal storage can raise the *cf* of a plant increasing the production of electricity, as well as reduce their dependency on the incentives to production from established legislative entities and specific directives.

IV. RESULTS AND REMARKS

Considering the proposed model in Fig. 6, a series of simulations of electricity production and operation have been conducted, which are parameterized according to the behavior of the electricity market and its possible regulation.

Fig. 7.1 and 7.2 show the results of the optimization of the generation for the proposed system with support of auxiliary energy in two intervals of simulation of 72h. The chosen sceneries correspond to periods in which the prices of sale of electricity vary due to the dynamics of the demand for electrical energy (high or low demand periods).

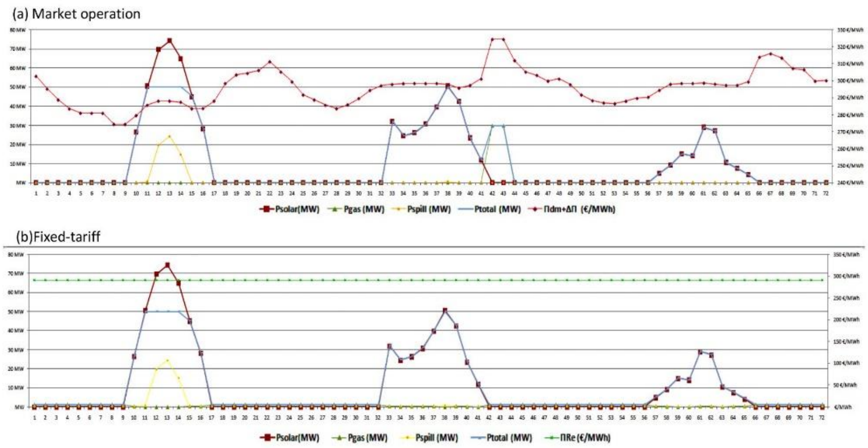

Fig. 7.1. Hourly program for optimal production. High Price rates.

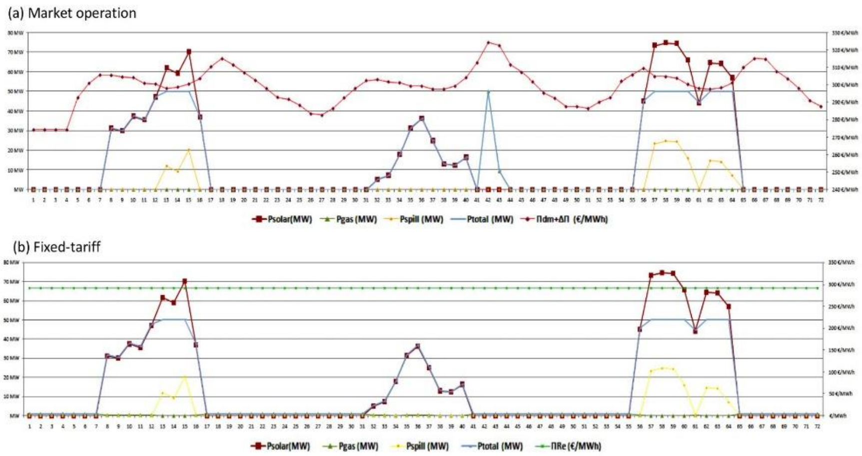

Fig. 7.2. Hourly program for optimal production. Low Price rates.

Table 3 shows the economic results of simulation of the operation for the PT plant basics in this work. For this model, it can be concluded that electricity generation will depend on the capacity of direct generation of solar concentrators, as well as on the available solar resource. In this case, the main factor that improves the economic benefit is the chosen economic regime for sales of electricity (either through a regulated rate or directly in the market sale). The differences in gross profit in the analyzed periods range between 7.44% and 11.68%, greater for sales to the market price. This difference is due to the selling periods of the energy when its price is higher than the equivalent fixed rate, making viable the use of auxiliary sources even for higher wholesale prices including their corresponding costs of use.

It is also possible to see that on a stage set with fixed prices, the use of an auxiliary source implies the increase of the cost operation due to the cost of the raw materials, without elements of decision of greater weight than the annual limit of provision of these auxiliary sources.

V. CONCLUSIONS

This work has analyzed the legislative developments toward deregulation as the optimization option of the energy production factor in the sector of renewable energy and, on the other hand, it has also traced its origin according to the European directives for markets of electricity.

The liberalization of the market of electric power has been developed with a great deal of economic support where the technologies used for the generation of installed power from renewable sources have not observed availability criteria of renewable resources and efficiency in electricity production expected. This phenomenon has led to the creation of an energy mix with oversized power factor and reduced production, given the scarcity of renewable resource for generation.

To get the optimization of the energy mix from renewable sources, some generation technologies offer higher regulatory power and adaptation with lower costs of production and operation, thus improving the economic viability of the investment.

Through the simulation of a PT plant, different scenarios of operation have been designed and analyzed, thus obtaining economic results contrasted with values from a currently operation plant.

TABLE 3. SIMULATION RESULT SUMMARY.

Period	Sales regime	Generated energy	Auxiliary energy	Income sale gross
Low Price rates	Free Market	761,18MWh	79,4MWh	224.640,25€
Low Price rates	Fixed Tariff	749,30MWh	47,2MWh	217.985,65€
High Price rates	Free Market	1033,21MWh	59,4MWh	312.821,68€
High Price rates	Fixed Tariff	1021,33MWh	47,1MWh	297.123,52€

The study of operation shows how the dynamics of generation can be adapted according to the target market (either free or regulated). The technical and economic analyses of production show that this type of renewable resource integration is possible for scenarios of low regulation (even in direct operation markets).

A complementary work will address detailed analysis of adaptation of each technology and renewable energy resource, which allows its adaptation to different markets and regulatory regimes.

NOMENCLATURE

cf	Capacity Factor (%)
PT	Parabolic Trough
CSP	Concentrating Solar Plant
P_{solar}	Capacity of power generation by solar resource (MW)
P_{gas}	Electricity generation by auxiliary gas boiler (MW)
P_{spill}	Spilling by collector defocusing (MW)
P_{total}	Total electricity generation (MW)
$\Pi_{dm} + \Delta\Pi$	Electricity energy price for deregulated market(€/MWh)
Π_{Re}	Electricity energy price for regulated market (€/MWh)

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ARTÍCULO 4

TECHNO-ECONOMIC ASSESSMENT OF HEAT TRANSFER FLUID BUFFERING FOR THERMAL ENERGY STORAGE IN THE SOLAR FIELD OF PARABOLIC TROUGH SOLAR THERMAL POWER PLANTS

ENERGIES, 2017, VOL. 10, NO 8, P. 1123. DOI: 10.3390/EN10081123.

Abstract

Currently, operating parabolic trough (PT) solar thermal power plants, either solar-only or with thermal storage block, use the solar field as a heat transfer fluid (HTF) thermal storage system to provide extra thermal capacity when it is needed. This is done by circulating heat transfer fluid into the solar field piping in order to create a heat fluid buffer. In the same way, by oversizing the solar field, it can work as an alternative thermal energy storage (TES) system to the traditionally applied methods.

This paper presents a solar field TES model for a standard solar field from a 50-MW_e solar power plant. An oversized solar model is analyzed to increase the capacity storage system (HTF buffering).

A mathematical model has been developed and different simulations have been carried out over a cycle of one year with six different solar multiples considered to represent the different oversized solar field configurations. Annual electricity generation and levelized cost of energy (LCOE) are calculated to find the solar multiple (SM) which makes the highest solar field thermal storage capacity possible within the minimum LCOE.

Resumen

Actualmente, las plantas de generación eléctrica mediante de colectores cilindro parabólicos (CCP), ya sean de producción directa o con bloque de almacenamiento térmico, utilizan el campo solar como un sistema de almacenamiento térmico para proporcionar capacidad térmica adicional cuando es necesario. Esto se hace mediante la circulación del fluido térmico por el sistema de tuberías del campo solar creando así un haz de fluido térmico. Así mismo, el sobredimensionamiento del campo solar puede dar lugar a un sistema alternativo a los métodos aplicados tradicionalmente de almacenamiento de energía térmica.

Este trabajo presenta un modelo de almacenamiento de energía en el campo solar de una planta de generación de energía eléctrica de 50 MW_e. Se analiza un modelo de campo solar sobredimensionado para aumentar su capacidad de almacenamiento térmico.

Se ha desarrollado un modelo matemático y se han llevado a cabo diferentes simulaciones durante un ciclo de un año. Se han considerado seis valores diferentes de solar múltiplo representando seis diferentes configuraciones de sobredimensionamiento del campo solar. La generación anual de electricidad y el costo nivelado de energía (LCOE) se han calculado para hallar el valor de solar múltiplo (SM) que hace maximice el almacenamiento térmico para un LCOE mínimo.

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Article

Techno-Economic Assessment of Heat Transfer Fluid Buffering for Thermal Energy Storage in the Solar Field of Parabolic Trough Solar Thermal Power Plants

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Academic Editor: George Kosmadakis
Received: 13 April 2017; Accepted: 24 July 2017; Published: 1 August 2017

Abstract: Currently, operating parabolic trough (PT) solar thermal power plants, either solar-only or with thermal storage block, use the solar field as a heat transfer fluid (HTF) thermal storage system to provide extra thermal capacity when it is needed. This is done by circulating heat transfer fluid into the solar field piping in order to create a heat fluid buffer. In the same way, by oversizing the solar field, it can work as an alternative thermal energy storage (TES) system to the traditionally applied methods. This paper presents a solar field TES model for a standard solar field from a 50-MW_e solar power plant. An oversized solar model is analyzed to increase the capacity storage system (HTF buffering). A mathematical model has been developed and different simulations have been carried out over a cycle of one year with six different solar multiples considered to represent the different oversized solar field configurations. Annual electricity generation and levelized cost of energy (LCOE) are calculated to find the solar multiple (SM) which makes the highest solar field thermal storage capacity possible within the minimum LCOE.

Keywords: solar thermal; parabolic trough (PT); thermal storage; heat transfer fluid (HTF) buffering

1. Introduction

Solar-only parabolic trough (PT) thermal power plants have been developed, improving generation over the years thanks to new designs and manufacturing processes. This core block of plant concepts—formed mainly for the solar field, fossil fuel boiler, and power block [1]—has evolved towards profitable installation by considering different solar radiation areas and different electrical markets [2,3]. One of the main developments was the storage system. This has always been present in the concept of solar thermal plants. In fact, as one of the first pilot plants in the world, Plataforma solar de tabernas (PST), was built with 6 KW_e of power generation in Almeria (Spain), starting operation in 1999 with a thermal storage system using direct solar steam. However, until the second half of the decade of the 2000s, there was no continuous investment in thermal energy storage (TES) blocks.

Thermal storage systems integrated into in thermal power plants provide the possibility of developing electrical power generation, improving intermittence, and increasing the profitability of the plant [4]. This is an important advantage, offering the opportunity to extend electricity production to periods without solar radiation by adapting the operation procedures. Presently, the total worldwide production using PT solar thermal power plants is over 3.7 GW_e; about 42% of these plants incorporate a TES system, with double-tank molten salt thermal storage systems being the most widespread design

Energies **2017**, *10*, 1123; doi:10.3390/en10081123 www.mdpi.com/journal/energies

concept as of the middle of 2016 [5,6] (see Figure 1). One of the newest PT solar power thermal plants, located in Córdoba (Spain), gives 7.7 equivalent hours of indirect thermal storage with double-tank molten salts. However, double-tank molten salt TES systems involve extremely high investment and maintenance costs. Although the number of hours of direct electric power generation increases notably [7], the elevated setup expenses, maintenance costs, and long investment payback period give rise to the need to study other TES systems. Heat transfer fluid (HTF) buffering using the solar field as thermal storage system is one of them.

Currently operating PT plants use the solar field as a HTF thermal storage system through an HTF buffer when it is needed, providing short-term storage capacity. This storage capacity is used mainly in two activities. On one hand, this prevents the oil from freezing and thus minimizes the effect of solar resource transient. On the other hand, extra storage capacity for the operation strategy of thermal plants is given. Oversizing the solar field enables the PT plant to increase the operating time at the design point.

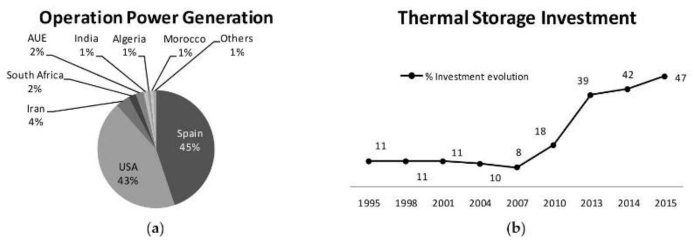

Figure 1. Currently operated parabolic trough (PT) power plants in the world (June 2016): (**a**) operating power generation by country; (**b**) double-tank molten salt thermal energy storage (TES) investment evolution in PT power plants [6].

The standard working temperature of thermal fluid (synthetic oil) in the solar field of existing plants is 393 °C. The HTF will be sent to the power block until its temperature in the solar field comes down below the minimum operating temperature (380 °C). An increment in the temperature of the thermal fluid achieves enhanced storage capability. This can be achieved by increasing the temperatures in the loops assigned to HTF storage to nearly its maximum operating temperature, 420 °C; or as a more profitable option, by working the entire solar field at this temperature. Long-term tests on the studied plants currently in operation have demonstrated that firstly, degradation for HTF at a circulating temperature of 420 °C is not significant; and secondly, no alteration in the integrity of the solar field has been evidenced.

It is possible to create storage systems with higher equivalent capacity (hours of thermal storage) than standard ones. HTF buffering consists mainly of using the overflow tanks, circulating pumps, HTF, and piping lines of the solar field as a thermal storage system. Once the operation intervals of each device involved in HTF buffering were analyzed, the security operation intervals of each device were been obtained without device arrangements. This analysis lets us determine the optimal strategy of operation using the common upper limits of the HTF buffering devices involved. During the nominal plant activity at sunrise, solar radiation is projected on the concentrating PT, where the direct normal irradiance (*DNI*) into thermal energy is transformed, heating the circulating working fluid in the solar field, which is conducted to the power block formed by a regenerative Rankine cycle used for electrical power generation. For periods of time apart from sunrise, even with shadows or partial overture, the system maintains the HTF in circulation into the solar field buffer for as much time as needed. The HTF buffering is restored using the thermal energy surplus in the solar field.

The solar multiple (SM) is defined as the ratio between the thermal power produced by the solar field at the design point of the power plant and the thermal power required by the power block at nominal conditions [8]. Therefore, the higher limits for solar field operation are determined by the SM of the power plant. However, this HTF buffering novel strategy using the common upper limits lets us improve energy production with the same solar radiation. The HTF buffering operation improves the generation curves in accordance with the market dynamics, increasing 3% through 12.5% of thermal energy for a given SM.

In reference to investment costs, it is known that for solar-only plants, the solar field represents the greatest investment [9]. For this reason, in other work [8] SM optimization is described. However, molten salt storage block investment plays an important role in the overall plant cost. Considering a value of SM of 1.4 and 3 h of thermal equivalent storage, double-tank molten salt cost increases the plant investment by 9.15% [10], representing a total of 19.20% of plant investment for equivalent storage sizes up to 7 h.

In the study of the HTF buffering TES system oversizing the solar field, a scheme of a solar thermal power plant is shown. An HTF buffering thermal storage system has been simulated using a currently operating plant model site in the south of Spain. Figure 2 shows a scheme of a solar-only PT power plant as the basis of this work. This large capacity model is described to present a thermal storage scheme as an alternative to presently operated storage systems. The plant model, database, and design-point conditions refer to the operated PT previously mentioned [11]. The quantification of variables, solar field dimensions, SM value, fired boiler, power block, and design-point conditions setup have been defined, taking the data from this real PT plant. The plant nominal electric power is 50 MW_e to comply with the Spanish renewable energy production law for concentrating solar power (CSP) plants [12]. Using the PT plant configuration mentioned before, a simulation model has been created considering the period of one year as a reference pattern. Thermal systems used in the models have been obtained from the PT power solar thermal plant.

Techno-economic assessment of HTF buffering for TES in the solar field of PT power plants is the main objective of this work, based on a real thermal power plant.

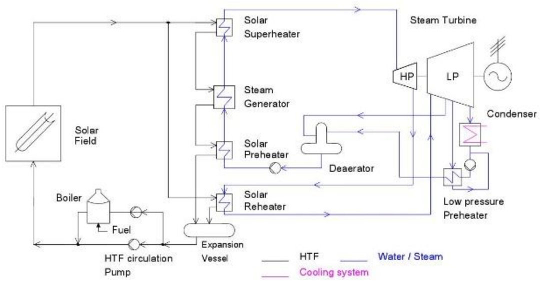

Figure 2. Solar-only PT and oil–steam thermal exchange. Heat transfer fluid (HTF); high pressure (FP); low pressure (LP).

2. Parabolic Trough Solar Thermal Power Plant

2.1. Direct Normal Irradiance on the Parabolic Trough Field

To estimate energy production in a solar thermal plant, a reliable prediction of solar radiation is needed. This radiation will affect the solar collector field to infer the capacity to generate electricity close to actual parameters. These predictions, often running several days in advance, allow operators of solar plants to estimate the electric energy production.

The use of weather forecasting models allows the power plant operators to obtain an electricity generation prevision once the parameters of solar radiation and meteorological interference of the plant are known with a degree of certainty.

To use predictions of radiation in the calculations, a simple prediction tool has been used which obviated the immediate meteorological parameters, allowing us to extend the period of study to a whole year, which in our case is the year 2015. The tool used, the "Simple Spectral Model for Direct and Diffuse Irradiance on Horizontal and Tilted Planes at the Earth's Surface for Cloudless Atmospheres" [13,14], was developed by the National Renewable Energy Laboratory (NREL; Golden, CO, USA) starting with a recent history of 10 years, and implementing a prediction algorithm with time resolution for the measurement and prediction of direct radiation, spectral irradiance, and energy received through the entire spectrum.

Historical values have been used for full solar radiation, measured relative to a unit area over a full day and throughout the study period. For a full year, with reference to the interval schedules, 8760 values were obtained from direct radiation with the specific location area of solar thermal plant located between parallels 37 N and 40 N [15]. The prediction accuracy is assessed using the mean absolute error (MAE). To generate results independent of power plant size, normalized error measures are used. The error measures are referred to as normalized mean absolute error (*NMAE*), defined by Equation (1):

$$NMAE = \frac{1}{N}\frac{\sum_{t=1}^{t=N}|R_{DNI}(t) - W_{DNI}(t)|}{R_{DNI}(t)}\ (\%), \tag{1}$$

Using the approximation method with historical data indicated above, it is considered that the *NMAE* index is practically unified.

Therefore, for this calculation, the prediction values with unitary probability considering the predicted direct irradiance $W_{DNI}(t)$ were taken using known values matching the time period t, to $R_{DNI}(t)$. The above approach allows for one uncertainty parameter in this model to remain unconsidered. The data obtained are analyzed by instantaneous and annual joint distribution [14]. Table 1 shows, for this location, the main parameters of solar radiation per square meter as a unit area. Figure 3 shows the solar irradiance per surface unit and wavelength.

Table 1. Main solar radiation data per square meter.

Parameter	Value	Unit
Solar field annual irradiance received	2664.5	kWh_{th}
Total heat radiated on the solar field	1148.4	kWh_{th}
Maximum thermal efficiency	70	%
Standard thermal efficiency	43.1	%
Hours of full load	8.6	Hours

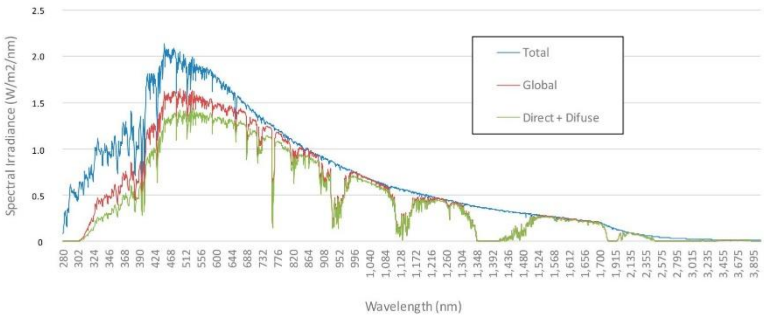

Figure 3. Solar spectral irradiance.

2.2. Collector Loop Configuration

PT collectors are concentrating solar collectors which convert the direct normal radiation into thermal energy, heating a working fluid to temperatures up to 550 °C. They are included within the category of medium temperature solar collectors. The limitation of temperature is imposed not only by the working fluid, 430 °C; but also by the maximum allowable temperature by the selective surface, 500 °C [16].

In the solar field, the solar module is composed by mirrors forming a strong structure. This structure has absorber tubes where the radiation is concentrated [17]. The solar module has standard dimensions 12.2 m long by 5.77 m wide. Any module individually considered is able to elevate the temperature of the oil to the rate at which fluid flows (about 3.5 m/s) by 2 °C.

To achieve an increase of temperature over 100 °C, it is necessary to group the collectors [18]. The collectors consist of eight modules with an approximate length of 150 m. The modules are linked together through the absorber tube. From a structural point of view, the PT modules consist of four main elements: the foundation and the support structure, PT reflector, the absorber tube or receiver, and solar tracking system [19]. Eurotrough is a steel support structure 12.27 m in length, called a "module", with a rectangular cross section holding the support arms of the facets of a parabolic mirror with a 5.76 meter aperture. This structure supports the mirrors with ceramic pieces.

The mission of the reflector PT solar collector is to reflect the solar radiation incident upon it and project this radiation by concentration on the absorber tube located in the focal line of the reflector [20]. The linear PT receiver, also called a heat collector element (HCE), is responsible for converting concentrated solar radiation into thermal energy carried by the thermal fluid. It is located in the focal line of PT concentrator subject to the support structure by arms. The solar field is the set of solar field loops and it is divided into smaller subfields because in times of high radiation, many loops are not required. Parabolic concentrating collectors are installed with their rotational axis oriented in the north–south direction [20].

2.3. Collector Loop Parameters

Although *DNI* can be intense, over 850 W/m^2 in a typical day [21] as shown in Figure 4, the energy utilization is only 175 MW of thermal capacity upon better reception. This is due to the interception factor K losses of the absorber tubes, the decrease of the effective capture area, and collector losses.

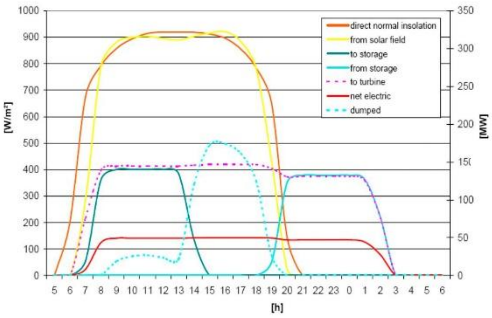

Figure 4. Hourly distribution of solar radiation during a typical day.

Sensitive meteorological data considered for the radiation study are: the hourly measurement of wind direction, speed, and frequency; the hourly measurement of temperature; the hourly measurement of ambient humidity; rainfall; overcast hours in a year; and monthly available water flow for cooling.

The local controller determines the position for the collector using a shade sensor which determines the sun position at any time, and with the aid of a mathematical algorithm by which the exact position of the sun any time of the year can be known with high precision, as set forth below. Equation (2) allows the evaluation of direct normal solar irradiance, A_a being the opening area (m^2) and θ being the incidence angle (degrees).

$$Q_{DNI-collector} = A_a \cdot DNI \cdot \cos(\theta) \quad (2)$$

2.4. Auxiliary Gas-Fired Boiler

The auxiliary fired boiler is responsible for maintaining the HTF temperature within the correct values for the system to continue running. With a thermal capacity of 35 MW_{th}, higher heating value (HHV) natural gas is the fossil fuel-type used. The possibility of using an auxiliary natural gas boiler is contemplated in the Spanish regulations [22] and limited by Law 24/2013 [23]. When the collectors do not provide enough thermal capacity during the production period, the gas boiler starts to work to maintain the HTF temperature to compensate the lack of solar radiation which may affect the planned electric energy delivery.

2.5. Power Block

The Rankine cycle of the power block applied to the PT solar thermal power plants is based on a cycle with superheating, reheating, and regeneration.

The steam circuit in a solar power plant consists of several elements described here (see Figure 2). The economizer (preheater), is where the water temperature at the working pressure of 100 bar(a) rises from 240 °C to a boiling point close to 310 °C. The evaporator (steam generator) is where the change of state of the water coming from the economizer occurs, generating steam at 314 °C and 104 bar(a) of pressure. The steam passes from the evaporator to the solar superheater. This forms the last stage of train steam generation, raising its temperature up to 385 °C, increasing its entropy in order to have the greatest possible turbine efficiency at the steam inlet. Finally, the solar reheater is the element responsible for collecting the gases from the discharge of the high pressure turbine at about 200 °C and constant pressure (about 18 bar(a)), raising its temperature to 380 °C and making it possible to dump the steam at the low pressure turbine. Solar intermediate reheating increases the Rankine cycle efficiency, reduces the steam moisture, and achieves a vapor flow reduction. However, the drawbacks are the greater length and higher investment cost of the turbine, additional costs, and pressure drop for the intermediate heater.

The working temperature of the oil directly influences the conception and design of the steam generation block. Temperatures below 400 °C limit the efficiency of the thermodynamic cycle, coming down to 40%. In addition, the working pressure is set around 100 bar(a), thereby preventing saturation vapor if it goes above this value, and there is a pressure drop if it is set below. Optimal configuration is commonly presented using a steam-generating turbine with two parallel bodies equally producing half of the total steam generated [24]. More precisely, this layout allows us to work at partial loads 0–50–100%, and presents two great advantages that lead to making to his choice. The first is that, in case of failure of one of the bodies, the other is always available and able to continue to produce electricity even if it is at a lower production capacity. The second is that at certain times with partial solar radiation, one of the turbines can use a more accurate approach at 100% load for such conditions, increasing efficiency.

3. Operation Management and Solar Thermal Plant Model

3.1. Annual Management Performance

All values of SM according to the annual electricity production have been calculated. This electrical power generation of the PT power plant is determined by the normal direct radiation values in direct dispatching, in addition to the derivative of TES in the solar field due to such solar radiation. Annual plant analysis was performed using a mathematical model. This model has been developed based on the ©THERMOLIB library (Aachen, Germany) [25]. A parallel simulation environment has been created in which data of provided solar radiation were introduced. The combined model is adapted to the characteristics of the proposed plant. The plant operation management is mainly based on four factors. Firstly, the nominal operation period is the time in which solar radiation above the minimum needed for the focused solar collectors provides enough heat to transfer the HTF to the power block. Second, the HTF buffering consigned by the estimated TES start time of the collectors is given by the estimated hourly values of direct normal radiation plus the estimated thermal capacity dumping period to the power block for electricity generation. Third, the fossil fuel boiler supports the plant operation at partial loads and for the plant cold starting. The fourth factor is total computation of the power block production hours in the grid coupling.

These factors, as well as the global daily efficiency, vary as the chosen operating strategy does, hence the importance of selecting the most appropriate operation strategy. It determines the way in which electricity power is produced [26]. Management operation performed by an optimization function is shown in the next section.

3.2. Plant Model

The reference values given in Table 2 are extracted from a real plant with coordinates 37°45′ N and 5°3′ W. These data are used in the plant model development based on the scheme of the solar-only PT powered thermal plant in Figure 2. The mathematical model of the PT plant shown in Figure 2 is used in a parallel simulation scenario with two models of power plants. A first scenario plant model is without TES; and a second one includes TES with HTF buffering in the HCE. Within this second scenario, a first stage considering the nominal SM of the plant has been simulated and the results are used for validation using data from the real plant. Different simulations of the plant according to six different values of SM have been performed.

Table 2. Capacity and sizing reference values for a 50-MW_e parabolic trough (PT) solar thermal power plant.

Capacity And Sizing Reference Values for Parabolic trough Solar Thermal Power Plants	
Solar field	
Number of trough collectors	312
Collector length (m)	148.5
Collectors by loop	4
Number of loops	78
Collectors total area	217,749 m^2
Solar multiple	1.0
Solar-thermal efficiency η_{Ct}	46.1%
Solar field losses c_{Ct}	<1%
Reaction turbine. Single recirculation, six steam extractors	
Nominal capacity	49.9 MW_e
Residual losses	5.0 MW_e
Power plant efficiency	37.5%
Steam conditions at turbine inlet point	100 bar(a) 370 °C
Steam conditions at recirculation point	16.5 bar(a) 370 °C
Steam nominal flow	59 kg/s
Operation set points	
HTF maximum temperature	430 °C
HTF freezing temperature	30 °C

Table 2. *Cont.*

Capacity And Sizing Reference Values for Parabolic trough Solar Thermal Power Plants	
HTF nominal operation temperature	260–393 °C
Solar field HTF inlet temperature	293 °C
Solar field HTF outlet temperature	393 °C
Solar field inlet HTF pressure	14–30 bar
Solar field outlet HTF pressure	10–15 bar
HTF at steam generator block (inlet/outlet)	393/293 bar
Total HTF mass	1050 tm
Annual solar field thermal energy received	422,166 MWh_{th}
Annual HTF system total thermal energy catch	181,531 MWh_{th}
Piping line thermal losses	6732 MWh_{th}
Solar field thermal efficiency	43%
Annual net electric energy production	60,835 MWh_e

The structure of the simulation environment is presented in Figure 5. The data acquisition program including economic parameters, HTF technical characteristics, and geographical and solar field data runs in the first instance; the optimization program is executed in parallel for each scenario of the plant described above.

Figure 6 shows the flow chart in which the solar field optimization algorithm for direct discharging and HTF buffering TES has been developed. The input data values, as 8760 dimension vectors, are introduced in a data acquisition module. The restrictions of total stored energy, maximum power generation, SM capacity, and HTF maximum temperature are introduced in the algorithm operation block. The operation algorithm detailed in Figure 7 allows us to obtain the optimized values for electricity.

The set of tabulated data are grouped and represented by a function that provides the results of computation. The solar collector algorithm used is obtained from a functional block responsible for collecting the solar radiation depending on the time and day of the year, from the data of direct normal solar radiation per unit area introduced from a table of external data.

The set of the solar field loops is modeled using a main basic unit affected by a linear operational amplifier at its input, which is replicated many times as available collectors in the solar field. The relationship between the number of collectors and the solar radiation received (global defocused model) is considered linear.

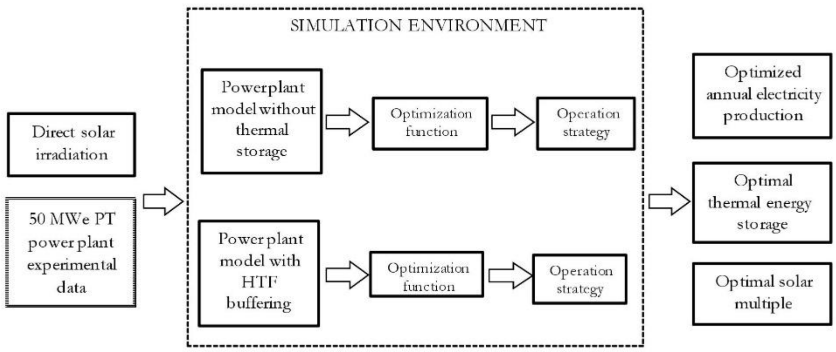

Figure 5. Structure simulation environment and data flow.

Simulation models run based on the results of the optimization function. These are:

(1) PT solar thermal power plant model with direct discharge, design set SM, and without a TES system in which electricity generation could differ beyond the thermal inertia of the system itself.
(2) Plant model with direct discharge, nominal SM, and without TES as described in the previous point, excepting the use of the HTF restraint systems as an energy buffer which would increase the solar field thermal inertia, obtaining a TES equivalent to several hours of electrical power generation, with a cost for thermal storage being rather small compared with other storage systems.

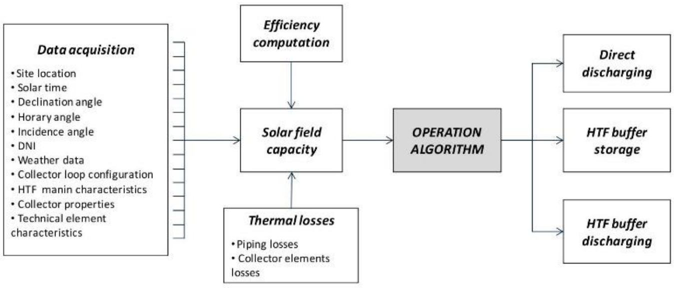

Figure 6. Performance solar field model flow chart for direct discharging and HTF buffering thermal energy storage (TES).

The plant operation algorithm defines the thermal energy sent to the power block, storage in the solar field, HTF buffering discharging, or a combination of both direct discharging and buffer storage. The gross electric energy generated is affected by the technical characteristics of the power block and electric generator elements. Finally, net electricity generation is the gross energy production subtracted by generation efficiency. Figure 7 shows the functional unit for power block and net electricity generation models.

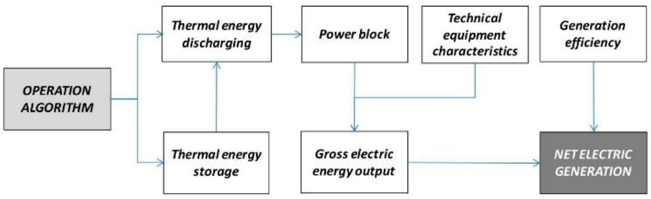

Figure 7. Functional unit for power block and net electric energy output models.

3.3. Model Validation

Once the description of the model plant was designed and its components were completed, the validation of the model simulation was performed by a reference data set from the solar power plant origin of this study, located at the coordinates 37°45′ N and 5°3′ W. The validation scenario chosen is a nominal condition solar-only plant (solar multiple = 1.2), without TES, and considering that the gas boiler is stopped. Solar radiation lower than 350 W/m^2, about 5922 h per year, is not considered enough to operate the power block and turbine. In contrast, with radiation higher than 650 W/m^2, about 370 h per year, HTF fluid always reaches the highest design point temperature, 393 °C, so as blur the solar field collectors is forced.

Validation of the mathematical model has been carried out by means of a bin hours method. A comparative analysis has been made taking into account the operating values. This method quantifies —by intervals—an absolute variable, which in our case is the direct solar radiation in the solar field per square meter. After grouping the direct normal radiation in intervals where the radiation received with the annual hours as part of each interval, the comparison between physical parameters of plant with those obtained by the model simulation is undertaken.

For the solar plant validation, HTF fluid parameters at the inlet superheater heat exchanger have been determined as the most significant features. Flow rate, temperature, and pressure values have been taken from the superheater inlet plant sensors and compared with the ones taken from the simulation model. One hundred measurements of solar radiation have been carried out for each parameter at the superheater inlet.

HTF temperature tends to be a fixed value along the plant operation in order to get the maximum efficiency. HTF fluid pressure keeps constant; expansion tanks maintain the fluid pressure within the solar field loops, helping to balance the system. Therefore, the plant makes continuous adjustments on the HTF fluid flow, trying to get the optimal fluid conditions at the power block input.

Table 3 shows the results of the HTF mass flow and temperature-averaged data series comparison using a bin hours yearly interval schedule. The 95th percentile applied to the results allows the statistical adjustment needed for data study and subsequent result validation. Thus, the harmonized results displayed show the concordance between the plant data and the model data. The uncertainty of the temperature is considered to be ± 1 °C, and ± 0.2 kg/s is the uncertainty of HTF mass flow in the real plant data, both given through metering devices. Data in Table 3 shows that, along low irradiance periods, the HTF temperature is below the set point. HTF mass flow varies widely from its highest value of 1400 kg/s with maximum solar radiation to the minimum value of 502 kg/s with lower solar radiation.

Table 3. Superheater inlet comparative series using a bin hours annual time schedule.

DNI (W/m^2)	Annual Hours	HTF Mass Flow (kg/s)			HTF Temperature (°C)		
		Plant Data	Model Data	Relative Error (%)	Plant Data	Model Data	Relative Error (%)
350–400	102	537.38	521.66	0.010	387.23	386.41	0.010
400–450	128	639.44	618.12	0.010	391.74	390.57	0.010
450–500	230	830.74	806.72	0.010	393.32	391.40	0.010
500–550	178	1077.45	1094.45	0.010	394.59	390.72	0.010
550–600	249	1291.90	1241.43	0.010	394.12	390.72	0.010
600–650	250	1361.43	1309.97	0.010	393.35	390.72	0.010

4. Heat Transfer Fluid Thermal Energy Storage Analysis as a Function of Solar Multiple

The appropriate SM value is based on a set of variables properly adjusted to each individual solar thermal power plant. For direct dispatching plants without TES, these variables are mainly the solar field components and size, plant location, and design conditions. In plants with any thermal storage system, the design's SM should be enough to offer a thermal energy surplus to the thermal storage block. The target of this study is to store thermal energy in the solar field, where the piping system acts by itself as a TES. For that proposal, system device losses in the piping system, collector area, circulating pump block, and plant performance in nominal operating conditions must be taken into account.

As shown in Figure 8, two working scenarios for the annual equivalent HTF buffering thermal storage energy as a function of SM have been carried out. The first scenario studies the equivalent hours of TES, considering an HTF buffering temperature of 420 °C in the storage loops and 393 °C (standard HTF temperature) for the rest of the solar field and power block HTF temperature input.

A second scenario considers an HTF temperature of 420 °C in the whole solar field, including the storage loops and the ones working for direct dispatching. Due to an SM higher than 1, during direct dispatching the PT plant can produce the nominal power while the HTF system is recharged by the solar field. During scarce or null radiation periods, the power block takes the thermal energy from the solar HTF buffering, reducing its temperature until maintenance limits.

The first scenario is mainly focused on the operation and maintenance plant modifications. The second scenario needs, besides the plant structural modifications of the first scenario, a special HTF for long round working periods at 420 °C.

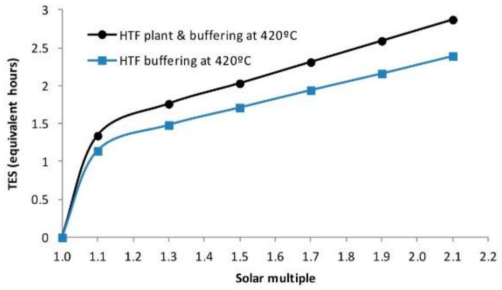

Figure 8. Averaged annual HTF buffering TES as a solar multiple function.

Figure 8 plots how the amount of equivalent thermal energy stored in the second scenario, where the HTF plant and the buffering are at 420 °C, which is proportionally higher than in the first scenario for all values of SM considered. Thus, second state will be used as a basis of this work.

For the present study, six values of SM have been considered. Each SM value leads to its corresponding TES as well as to different sizes of solar fields. The collector area varies depending on the solar field size. Averaged *DNI* values and plant operability vary depending on the time of year. Finally, TES and thermal losses in the piping line vary depending on both the size of the solar field and the time of year. Annual HTF buffering thermal storage size, thermal losses in piping line, and solar field size have been calculated as a function of SM.

Table 4 shows the average annual values of TES and solar field oversize for different SM values. The increase in SM increases the capacity loss in the piping. This is due to the increasing number of solar collectors and the greater number of operation hours of the solar field. Thus, thermal energy losses to be considered are both losses during the daytime operation and the corresponding HTF buffer discharge during overcast sky or sunset periods. The TES in the solar field increases as the SM is greater. Full load TES data in Table 4, both in daily absolute terms (MWh_{th}) and equivalent hours of thermal storage, can be used for a comparative study of other thermal storage systems, serving as a foundation for future work.

Table 4. Thermal energy storage and collector area oversize as a function of solar multiple.

SM	TES (Equivalent Hours)	Net Daily TES (MWh_{th})	Thermal Losses in Piping Line (kW_{th})	Net Power Block Thermal Demand (MW_{th})	Collectors Area (m^2)
1.1	1.14	164.38	239.523	143.75	239,524
1.3	1.49	213.69	2830.72	143.75	283,074
1.5	1.72	246.57	3266.24	143.75	326,623
1.7	1.94	279.45	3701.72	143.75	370,173
1.9	2.17	312.32	4137.29	143.75	413,723
2.1	2.40	345.20	4572.71	143.75	457,273

5. Economic Analysis

Economic analysis is focused on the most profitable operation situation, which is the second scenario described in the previous section. The average lifetime levelized cost of electricity (LCOE) is determined for different values of SM [27]. An economic assessment which has been used to compare the costs of electric energy production according to the different values of SM is considered. The costs of fossil fuel to feed a gas boiler have been considered in our conception of LCOE. Equation (3) is used to obtain the value of LCOE for the different considered solar power plant configurations:

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + O\&M_t + F_t)}{\sum_{t=1}^{n} E_t}, \quad (3)$$

The capital cost in the year t is calculated in Equation (4):

$$I_t = crf \cdot I_c, \quad (4)$$

The capital recovery factor is calculated according to Equation (5):

$$crf = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} - k, \quad (5)$$

where i is the debt interest rate; n is the depreciation period; k is the annual insurance rate; $\sum_{t=1}^{n}()$ is the values buzzer along the depreciation period; I_c is plant investment cost; $O\&M_t$ is the combined fix and variable operation and maintenance cost in the year t which can be calculated as $O\&M = O\&M_{fix.t} + O\&M_{var.t}$; $O\&M_{fix.t}$ is the operation and maintenance cost referenced to the plant capacity; $O\&M_{var.t}$ is the operation and maintenance cost referenced to the electric energy production; F_t is the fuel consumption cost in the year t; and E_t is the net electric energy production in the year t.

Main data assumptions used for economic analysis are shown in Table 5. The main data baseline has been taken from [28]. Cost due to investment, fixed and variable operation, and maintenance and fuel consumption are different according to the SM dimension as this value directly affects the size of the solar field, the amount of electricity generated, and fuel consumption. The data in Table 5 have been estimated considering a depreciation period of 25 years and a debt interest rate of 8.0%.

Table 5. Main data for PT solar thermal power plant levelized cost of electricity (LCOE) calculation (solar multiple, SM = 1) [29]. O&M: operation and maintenance; higher heating value (HHV).

Concept	Value
Site cost (€/m^2)	13.33
Solar field investment (€/m^2)	213.52
HTF system (€/kWh$_{th}$)	210.95
Power plant investment (€/kW$_e$)	643.20
Investment indirect cost and contingencies surcharge (%)	16.00
Fixed O&M cost (€/kW$_e$/year)	45
Variable O&M cost. (€/MWh$_e$)	3.50
HHV natural gas fossil backup price (c€/kWh)	2.87
Debt interest rate (%)	8.00
Annual insurance rate (%/year)	0.50
Capital recovery factor (%)	8.38
Plant lifetime (n)	25

Economic results for six values of equivalent full load TES are shown in Table 6. For the power block, 40% average conversion efficiency has been considered, as well as 20% of thermal capacity fraction for standby and startup. Sensitivity parameters analysis shows that the investment cost increases with the size of the solar field due to the increased in the number of collectors such as the pumping system and its auxiliary elements. Meanwhile, the cost of operation and maintenance are also enhanced by the oversized solar field, mainly due to the increased number of maintenance operations caused by the increased of the solar field size and the plant operation hours.

The gas boiler's main use is based on the first startup operation of any day as well as for covering the solar radiation fluctuations along the day. Thus, fuel consumption costs increase as the TES does; this is due to the fact that, as the solar field size is greater, a higher boiler runtime is needed to retain the HTF temperature within the correct margins for performance over time.

Table 6. Economic results for a 50-MW_e PT power plant with heat transfer fluid (HTF) buffering thermal storage as a function of the solar multiple.

Solar Multiple Value	1.1	1.3	1.5	1.7	1.9	2.1
HTF buffering TES (equivalent hours)	1.14	1.49	1.72	1.94	2.17	2.40
Solar field area (m^2)	239,524	283,074	326,623	370,173	413,723	457,273
Investment cost per year (M€)	6.34	6.66	7.34	8.03	8.72	9.40
Annual O&M cost (M€)	2.61	2.68	2.79	2.88	2.98	3.03
Annual fuel consumption cost (M€)	0.015	0.017	0.019	0.022	0.024	0.027
Annual net electric energy production (GWh_e)	90.51	103.39	120.75	134.77	147.61	156.73
Capacity factor (%)	19.46	23.65	27.62	30.83	33.77	35.85
Annual LCOE (€/MWh_e)	185.03	160.96	150.65	146.39	144.05	145.23

Figure 9 shows the HTF buffering thermal storage as a function of the SM. The curve implies high efficiency of HTF buffering considering a SM greater than 1.3.

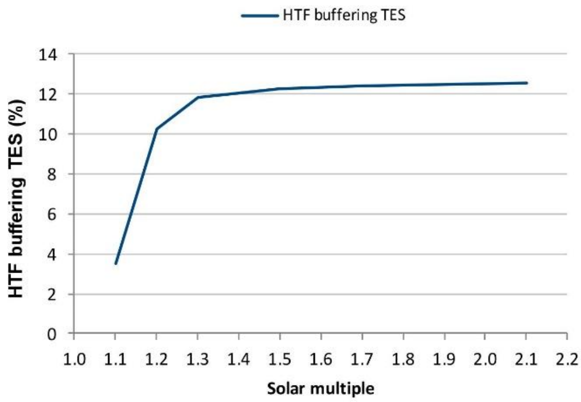

Figure 9. HTF buffering thermal energy storage by solar multiple value.

As commented in other works, for solar-only plants, defocusing collectors are used when the SM is higher than one [30]. Furthermore, an SM of about 1.3 is found to minimize the LCOE. As shown in Figure 10, HTF buffering thermal storage extends the plant operating time, thus increasing the capacity factor. For common design plants with SM = 1.3, HTF buffering enables a capacity factor of 23.65%. This value is significantly higher than plants with direct discharging traditional operating mode [9], where capacity factor is around 16%. The best results are achieved for solar higher multiple values where the capacity factor reaches levels of 35.85% for SM = 2.1.

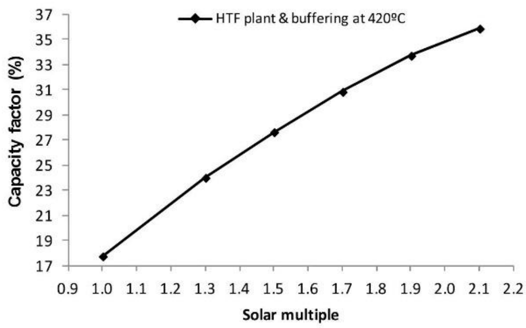

Figure 10. Thermal power plant capacity factor by solar multiple value.

As well as improving the capacity factor, HTF buffering enables diversion of the energy into thermal storage as shown in Table 6. The electricity production and the LCOE evolution values according to SM are shown in Figure 11. The electrical generation increases at the same time as the field size does, increasing by 156.73 GWh_e with SM = 2.1.

However, the LCOE decrease reaches a critical point at SM = 1.9 and 144.05 k€/GWh_e, with LCOE being 145.23 k€/GWh_e for SM = 2.1. It breaks its downtrend and tends to increase. Hence, plant electricity production is not able to offset the investments in the solar field and O&M for SM over 1.9. This is mainly because the collector system is not suitable for very long-term storage capacity when sufficient insulation is not provided, and pass heat losses make the HTF temperature decrease gradually until reaching non-operational temperature points.

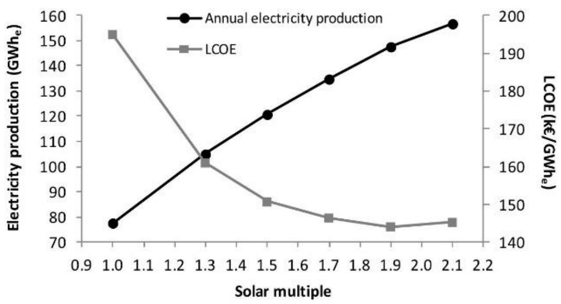

Figure 11. Annual net electricity production and levelized cost of energy as a function of the solar multiple.

The optimal thermal storage value is the one which obtains the highest electricity production with a minimum cost of electricity. Electricity market price factors and grip operation strategies have not been taken into account in this study, providing a basis for further works. According the parameters considered, an SM value of 1.9 is the most profitable size in order to obtain the maximum capability to the thermal power plant. Values of SM below 1.3 and above 1.9 carry a non-trend cost of energy decreases, as shown in Figure 11, leading to collector configurations far from the optimal solar field design.

6. Discussion

As shown in Figure 10, an increase of annual electric energy generation gives rise to higher solar-to-electric efficiency as the SM enhances. With respect to the LCOE, it is noted that its value decreases when increasing the value of the SM up to SM = 1.9, where trends towards growth are mainly influenced by the high cost of the solar field investment and solar field performance loss, as seen in Table 6. Figure 11 represents the annual net electricity production and LCOE as a function of the SM, where SM = 1.9 obtains the maximum capability according to the plant capacity (50 MW_e) and location (between parallels 37 N–40 N) which are basic to this work. For a solar field size of 1.9, electricity generated and LCOE are 147.61 GWh_e and 144.05 k€/GWh_e, respectively. These values of yearly generated energy and LCOE have been improved 8.54% and 6.01%, respectively, in comparison with the values from the power plant simulated without HTF buffering.

The results obtained are given without considering methods of operation of the electricity market. Thereby, a constant electricity demand has been taken without the electricity price being affected by incentives from the market. Besides, the consequences associated with the solar field oversizing in terms of heat losses, pressure drop and pump unit size increments in the pipe line, efficiency of the whole system, and the useful operating hours of the gas boiler have been considered. The method described in this study can be used as a basis for analyzing the HTF buffering performance of specific plants, either currently operated or at the design stage; with each adapted to its SM singular value.

7. Conclusions

An innovative and available thermal storage methodology using the solar field as a heat fluid buffer has been carried out. As a first scenario, a 50-MW_e solar-only PT power thermal plant model was created, corresponding to a specific area located between the parallels 37 N and 40 N.

The plant model, using different nominal preset SM values, was simulated for a period of one year as a direct dispatch from the solar field to the power block, using the solar field as TES through an HTF buffer. Using currently operated plant data acquisition, the model has been validated and data have been calibrated.

The second scenario proposed increased the HTF working temperature in the solar field to 420 °C. This working temperature is taken as the basis for further calculations, allowing higher throughput in the TES. The effect of different SM values on the electricity power generated, its equivalent hours of TES, capacity factor associated, and LCOE have been analyzed. The increase in the operating and maintenance costs and a significant increase in losses in the piping line are offset by the improved fostered energy storage.

Acknowledgments: The authors would like to thank Elena Gómez for proofreading and English correction of the paper.

Author Contributions: Jorge M. Llamas and David Bullejos conceived and designed the mathematical model and its calibration, they also developed the environment of study and simulation model; Manuel Ruiz de Adana helped with the simulation model and performed the calibration model process; Jorge M. Llamas and David Bullejos analyzed the data; Jorge M. Llamas wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Variables

crf	Capital recovery factor (%)
EPw_t	*DNI* capacity vector for the period t (MW_{th})
H_{local}	Local specific time (s)
Hs	Solar reference time for any land installation (s)
I_t	Capital cost in the period t (€)
$LCOE$	Annual levelized cost of energy (€/MWh_e)

N	$NMAE$ study from period 1 to N (dimensionless)
$NMAE$	Normalized mean absolute error (%)
$O\&M$	Annual operation and maintenance cost (M€)
$Q_{DNI-collector}$	Thermal energy received by the collector (kWh_{th})
$R_{DNI}(t)$	Real direct normal radiation in the period t (W/m^2)
TES	Thermal energy storage (MWh_{th})
$W_{DNI}(t)$	Predicted direct normal radiation in the period t (W/m^2)
δ_s	Declination angle (deg)
θ	Incidence angle (deg)
Ω_t	Direct normal irradiance capacity vector for the period of study (MW_{th})
ϖ_s	Hour angle (deg)

Acronyms

CSP	Concentrating solar thermal power
DNI	Direct normal irradiance
HCE	Heat collector element
HHV	Higher heating value
HTF	Heat transfer fluid
PT	Parabolic trough
SM	Solar multiple

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ARTÍCULO 5

OPTIMAL OPERATION STRATEGIES INTO DEREGULATED MARKETS FOR 50 MWE PARABOLIC TROUGH SOLAR THERMAL POWER PLANTS WITH THERMAL STORAGE

ENERGIES, 2019, VOL. 12, NO 5, P. 935. DOI: 10.3390/EN12050935.

Abstract:

The evolution of electric generation systems, according to relevant legislation, allows for the parallel evolution of the installed power capacity of renewable resources with the development of technologies for renewable resources, therefore optimizing the choice of energy mix from renewable resources by prioritizing the implementation of concentrating solar thermal plants.

Thanks to their great potential, parabolic trough solar thermal power plants have become the most widely spread type of electricity generation by renewable solar energy. Nonetheless, the operation of the plant is not unique; it must be adapted to the parameters of solar radiation and market behavior for each specific location. This work focuses on the search for the optimal strategies of operation by a mathematical model of a 50 MW_e parabolic trough thermal power plant with thermal storage. The analysis of the different ways of operation throughout a whole year, including model verification via a currently operating plant, provides meaningful insights into the electricity generated.

Focused to work under non-regulated electricity markets to adjust this type of technology to the European directives, the presented model of optimization allows for the adaptation of the curve of generation to the network demands and market prices, rising the profitability of the power plant. Thus, related to solar resources and market price, the economic benefit derived from the electricity production improves between 5.17% and 7.79%.

Resumen:

Los avances en los sistemas de generación eléctrica junto a un favorable marco legislativo, permiten la evolución paralela de la energía instalada procedente de recursos renovables con el desarrollo de tecnologías que mejoren el aprovechamiento de estos recursos, optimizando así la combinación energética a partir de recursos renovables priorizando la implementación de plantas termosolares de concentración.

Gracias a su elevado potencial, las plantas termosolares de colectores cilindro-parabólicos se han convertido en el tipo de generación eléctrica procedente de energía renovable más extendida. Sin embargo, el modo de operación de la planta no es único, se debe adaptar a los parámetros de radiación solar y comportamiento del mercado eléctrico para cada localización. Este trabajo se centra en la optimización de las estrategias de operación mediante el uso de un modelo matemático basado en una planta termosolar de colectores cilindro-parabólicos de 50 MW_e con almacenamiento térmico. El análisis de los diferentes modos de operación a través de un ciclo anual, incluyendo validación del modelo, proporciona información significativa de la capacidad de generación eléctrica.

Enfocado a trabajar bajo un mercado eléctrico no regulado para adaptar este tipo de tecnología a las Directivas de la Unión Europea actuales, el modelo de optimización presentado permite la adaptación de la curva de generación a las demandas de la red eléctrica y a los precios de mercado, aumentando la rentabilidad de la central de generación. Así, en relación con los recursos solares y el precio de mercado, el beneficio económico derivado de la producción de electricidad mejora entre el 5,17% y el 7,79%.

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Optimal Operation Strategies into Deregulated Markets for 50 MW_e Parabolic Trough Solar Thermal Power Plants with Thermal Storage

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Received: 17 February 2019; Accepted: 6 March 2019; Published: 11 March 2019

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Abstract: The evolution of electric generation systems, according to relevant legislation, allows for the parallel evolution of the installed power capacity of renewable resources with the development of technologies for renewable resources, therefore optimizing the choice of energy mix from renewable resources by prioritizing the implementation of concentrating solar thermal plants. Thanks to their great potential, parabolic trough solar thermal power plants have become the most widely spread type of electricity generation by renewable solar energy. Nonetheless, the operation of the plant is not unique; it must be adapted to the parameters of solar radiation and market behavior for each specific location. This work focuses on the search for the optimal strategies of operation by a mathematical model of a 50 MW_e parabolic trough thermal power plant with thermal storage. The analysis of the different ways of operation throughout a whole year, including model verification via a currently operating plant, provides meaningful insights into the electricity generated. Focused to work under non-regulated electricity markets to adjust this type of technology to the European directives, the presented model of optimization allows for the adaptation of the curve of generation to the network demands and market prices, rising the profitability of the power plant. Thus, related to solar resources and market price, the economic benefit derived from the electricity production improves between 5.17% and 7.79%.

Keywords: solar thermal; parabolic trough; thermal storage; model validation; electricity market; operation strategy

1. Introduction

At present, the generation of electricity by renewable resources from solar energy depends on solar availability, regardless of the specific plant location and the electrical market. The selection of parameters and specific variables, such as storage capacity, reception surface, or generation systems, allows high efficiency proposals for optimal operation to be obtained [1].

Nevertheless, the current trend of solar thermal power plants is to assume the characteristics of the electricity market, either regulated or free, according to each location. The adaptation of generation-to-demand therefore improves the integration of solar thermal energy into the electricity market [2].

This work presents an analysis of and the plans for power generation by a parabolic trough (PT) solar thermal power plant, enabling better integration into the grid, as well as a presentation of the best offers on the most favorable periods of purchase price [3].

Energies **2019**, *12*, 935; doi:10.3390/en12050935 www.mdpi.com/journal/energies

In [4] a thermal model of electricity production by renewable resources is developed. In [5] an optimization model is used to calculate the cost-effectiveness of PT plants' solar heating systems through different constructive hypotheses and operations. However, the relationship with the physical model of the plant is not described in this work.

The optimization procedure mentioned in [6] includes the equations corresponding to the physical parameters of the solar plant, although the optimization method and its equations are not detailed. This reference shows the curves of the operation of the plant and its power output for some days, without detailed reviews of the results obtained.

In [7], the optimum behavior of plants in isolated days is shown, neither showing the equations of the model of optimization nor providing a comprehensive assessment of the benefits obtained. In [8], the proposed optimization in production models starts from a simplified hypothesis of operation that does not serve the technical limitations inherent to the operation of the plant. In all these cases, the optimization method would require a complete modeling of the solar plant and an adjustment of the equations corresponding to this model.

The main objective of this work is the optimization of the operation procedures of PT Plants, where both the exchange of production rules and the reduction of economic support have forced the optimization of production of electricity, according to the dynamics of the plant, to consider the sale of energy in free markets, where prices depend on supply and demand. According to these needs, this study began with fieldwork in a real plant, located in Córdoba (Spain), using a double tank molten salts system for thermal storage. The plant of study has 50 MW of net electrical power and directly operates in the Spanish electricity market. Through the construction of the plant model, and its subsequent validation, it will be possible to analyze production situations based on solar radiation parameters, thermal storage, and generation dynamics. This previous analysis of different scenarios allows for the evaluation of strategies to obtain a greater generation volume, under better economic conditions.

2. Materials and Methods

2.1. Solar Thermal Power Plant and Thermal Energy Management

2.1.1. Solar Field and Heat Transfer Fluid (HTF)

The economic benefit and reduction of costs by the implementation and maintenance of the solar field are directly related to the layout of the thermal fluid transport systems. The use of efficient technologies that minimize layout spaces has a significant impact on the performance and loss coefficients of the final installation. As shown in [9], the low uniformity of solar capture in the field, due to different parameters and meteorology, makes it necessary for collectors to use partial blurs or loops that increase the transient effect of solar capture, making the operation of the real PT plant more difficult. Likewise, it is necessary to know the actual absorption conditions in large loops of collectors with an exhaustive control of the temperature of each component in the loop [10]. The inspection systems of these concentrators allow for analysis of the degradation of materials, thermal losses, and losses of vacuum [11].

In [12], a solar thermal plant with 15 h of capacity in thermal storage and a turboalternator of 20 MW_e, which needs a collection surface of 250,000 m^2 with parabolic receptors to generate a power of 120 MW_{th}, is presented. About 1,000,000 m^2 of the whole surface of the solar plant has been analyzed. For this sizing, a high capacity factor (CF) has been demonstrated. Furthermore, a low dependence on supporting fossil fuels is obtained, thus reducing the levelized cost of electrical energy production (LCOE).

The design of the paths must reduce losses as much as possible, as well as enable the maximum generation on demand, with short-duration peaks and acceptable thermal inertia [13].

In relation to HTF, the oil normally used in current PT plants is Therminol VP-1, an eutectic mixture of diphenyl and diphenyl oxide [14]. This synthetic oil works efficiently at 400 °C, although its freezing point is 12 °C, which obliges maintaining the whole oil circuit at a constant temperature above this value. The PT Plant oil type considered for this work is Therminol VP-1. The range of working temperatures with PT collectors is 150 °C to 420 °C. For higher temperatures, thermal losses in these types of collectors are high, reaching the degradation of the material at 420 °C.

2.1.2. Thermal Storage System

The Direct Storage System shown in Figure 1 has two tanks of thermally insulated molten salts (hot tank and cold tank) in which the entire fluid is contained [15]. During the loading process, the molten salt in the hot tank raises its working temperature by heat exchange with the HTF from the solar field. In the discharge process, the molten salt transfers its energy to the power block.

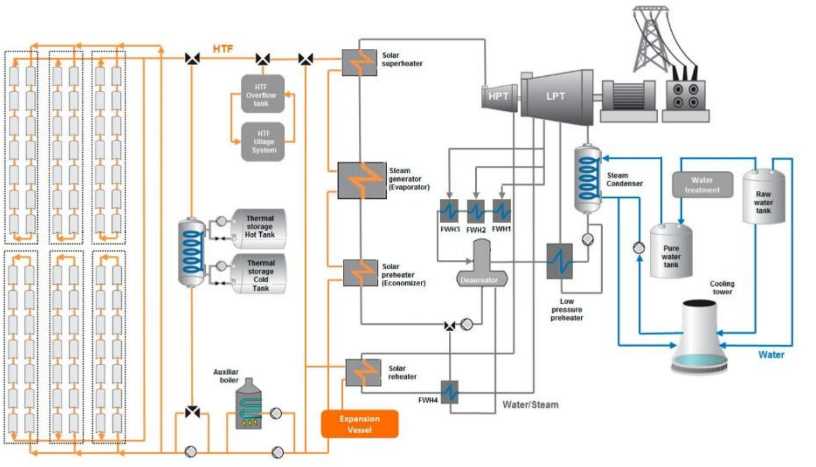

Figure 1. Double tank direct storage system.

The storage in two tanks is essential when fluids of relatively high thermal conductivity, such as sodium and molten salts, are used. Due to its capacity and characteristics, this system is the most common for PT plants and is the one analyzed in the present work.

The storage system, using a double tank and molten salt as a thermal exchange fluid, is usually called a Delayed Intermediate Production System (DIPS). For a storage system with an autonomy of 6 h with maximum power, the equivalent energy storage of 1010 MWh_{th} is required, as shown in Table 1.

The mathematical model for the PT Plant implements the generation and storage operation mode with sufficient solar radiation (7 $kWh/m^2/day$) [16] or the generation and recovery mode for minor radiation levels.

This type of plant would correspond to the system of production of an intermediate load with a DIPS storage system and with periods of operation at peak load (PLP - Peak Load Plant). The average operation time of this model in regime of production, production storage, and production recovery is 2159 h per year.

2.1.3. Reference Values for the PT Plant Model

In Table 1 the main reference design values for a 50 MW_e PT Plant with thermal storage by molten salt is shown [17]. The information therein will be used to configure the mathematical model proposed for the plant. These parameters vary among plants, taking into account the solar collection capacity and oversizing by solar multiple (SM), as well as the capacity of thermal storage (equivalent hours of electricity production) [18,19].

Table 1. Reference design values for a 50 MW_e PT plant with thermal storage.

Solar Field		
PT Collectors	Units	624
Total collectors' surface	m^2	475438
Solar Multiple	-	2
Solar-thermal efficiency $\eta_{Ct}(\eta_{Solar})$	%	51.6
Solar field loses c_{Ct}	%	<1
Operation average temperatures	°C	260–393
Solar field input temperature	°C	293
Solar field output temperature	°C	393
Pressure in checkpoints		
Thermal fluid pumps output	bar	15.30
Solar field input	bar	14–28
Solar field output	bar	10–15
Steam generation system input/output	bar	393/293
Molten salt exchange input/output	bar	293–380
Yearly received thermal energy	MWh_{th}	1090000
Total thermal energy collected by the HTF system	MWh_{th}	465000
Collectors thermal efficiency	%	43
Total average efficiency	%	16
Thermal Storage (Double Tank of Molten Salt)		
Total storage capacity	MWh_{th}	1010
Storage efficiency $\eta^{+}(\eta_{HEDFromSt})$	%	98
Storage recovery efficiency $\eta^{-}(\eta_{HEDToSt})$	%	97
Steam Turbine. Single Recirculation, 4 Steam Extractions		
Nominal electric power	MW_e	49.9
Residual loses	MW_e	5.0
Efficiency $(\eta_{DTurbineGross})$	%	99
Net energy production	MWh_e	160000
Input steam to turbine	bar	100 (370°C)
Recirculation	bar	16.5 (370°C)
Steam nominal flux	kg/s	59

2.2. Mathematical Model and Optimization

For the study of the operation and optimization of the solar plant, as well as for the construction of the different operation models for the plant, the plant operation and electricity market parameters have been considered. The first ones have been taken from the analysis of the characteristics of the PT plant, as well as from the detailed study of the elements that should be introduced in the design of an operation model. Next, the market parameters show the obtained operation limitations of the model in order to adapt it to the needs of the network of supply, independent from the generation, technical viability, or availability of potency.

For the achievement of the present study and the optimization of a model of electrical production, the economic information and solar radiation correspond to the year 2017 [20]. The known data for prices and production allow us to validate the model of production, which is possible through prediction tools.

2.2.1. Mathematical Simulation Model

In order to optimize the operation strategy, a plant model has been designed using the ©THERMOLIB library [21]. Starting from initial data on solar radiation, electricity price in the market, and nominal parameters of the plant, the operation parameters, such as the amount of thermal energy to be stored, the amount of thermal energy to be recovered, the degree of defocusing of the collectors, the thermal energy flow of the plant, and the final energy generated are obtained.

Created in ©MATLAB [22], the structure of the model proposed for this plant is presented in accordance with its architecture and operation mode. The use of a parallel simulation structure will allow for comparison of the different solutions adopted by minimizing the complexity of the data comparison processes, as well as the storage of the same ones. Figure 2 shows the structure of the simulation environment, with detail of the input and output data flow in each execution. Furthermore, the calibration of the model using data from the current plant validates the tools used.

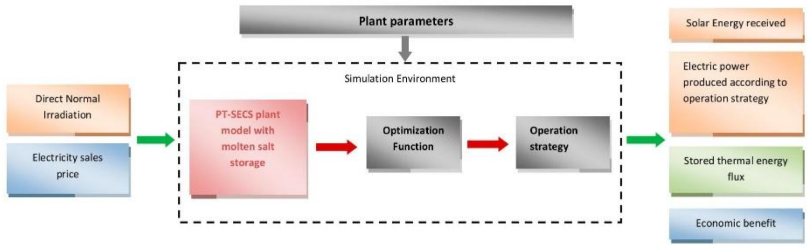

Figure 2. Structure of the simulation environment and data flow.

The solar collection model used was obtained from a functional block in charge of collecting the solar radiation depending on the time and day of the year, starting from direct solar radiation per unit of area data and introduced from the external data table. The set of links that make up the solar field have been modeled using a basic unit that consists of an operational amplifier linear to its entry, which would replicate as many times as there are collectors in the field, which for the simulated plant is 624. The relationship between the number of collectors and the solar radiation received (model of global blur) was considered linear.

The plant operation algorithm defines the thermal energy sent to the power block, storage in the solar field, HTF buffering discharging, or a combination of both direct discharge and buffer storage. The gross electric energy generated is affected by the technical characteristics of the power block and the electric generator elements. Finally, net electricity generation is the gross energy production subtracted by the generation efficiency. Figure 3 shows the functional unit for a power block and the net electricity generation model [19].

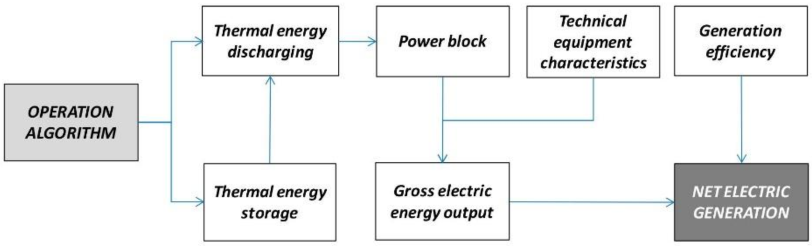

Figure 3. Functional unit for power block and net electric energy output models [19].

2.2.2. Implementation of the Model in Real PT Plants

The implementation of the mathematical model and optimization in a 50 MW PT plant must be done by a system of continuous simulation. It is necessary to introduce the hourly updates of corrections in the matrix of vectors of the model due to deviations in final solar radiation, final prices of market, energy accounting in the storage system, and electric power finally produced. The results of production shown in this work were obtained after the execution of the model without feedback by deviations, considering real results were not available. This supposes the execution of the model of the plant over two vectors of 8760 values, corresponding to the solar radiation available and the price of the electricity on market. The first was obtained using a predictive model and the second one through historical values.

The proposed model uses a total of 67 parameters of positive real values and 25 continuous variables described in Equations (3)–(7), formed by vectors of 8760 elements of real numbers. The optimization function used 8 variables ($R_{DNI}(j)$, A_{Ct}, $P_A^+(j)$, $P_A^-(j)$, $E_A(j)$, P_{SpillI}, and $\Pi_{DM}(j)$) formed by vectors of 8760 elements of real numbers.

Calibration of the PT Solar Thermal Power Plant Model

The validation of the model is required to determine if the model is a good representation of the system. The proposed method of validation is the calibration of the model in a process of comparing the behavior of some of its significant variables with the behavior of them in the real system of the plant. For this validation, real data from "La Africana Energía" PT solar thermal plant, located in Cordoba (SPAIN), have been used. After completing this process, it is possible to determine whether the proposed model can anticipate the behavior of the real system in a reliable way.

For the validation of the model, it is necessary to consider that the operation depends on physical, economic, and logistics factors. Some of them, being fundamental criteria for the operation of the PT solar thermal power plant, have been identified as significant parameters. Two of them are the mass flow of synthetic oil at the exit of the pressure group in the solar field and the temperature of the fluid at the same point.

In order to analyze the correspondence between actual and obtained values using the plant model it is necessary to analyze the coefficient of determination (R^2) which allows the percentage of the total variation observed in each of the compared variables to be determined. To do this, the first step is calculating the Pearson correlation coefficient according to Equation (1), which will indicate the type of correspondence between the data analyzed. The two compared variables, HTF temperature, and flow rate, are chosen in pairs using a bin hour yearly interval schedule [19].

$$r = \frac{\sum (x_i - x)(y_i - y)}{\sqrt{\sum (x_i - x)^2 \sum (y_i - y)^2}}, \quad (1)$$

where X_i and Y_i are the values of X and Y for the individual i.

The correlation coefficient gives the percentage of points of the group that comply with the correlation between the values of the plant and the model, according to the dispersion curves shown in Figures 4 and 5. The results of correlation of the analyzed data are summarized in each figure.

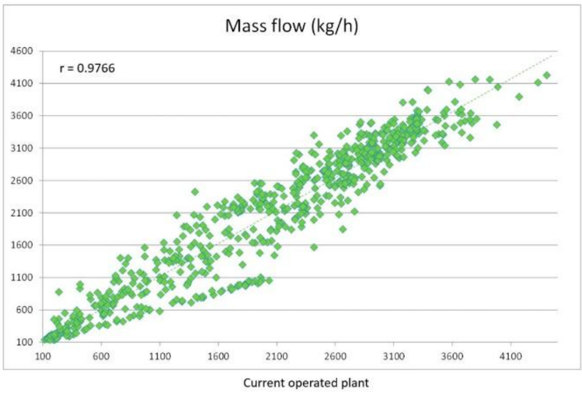

Figure 4. Representation of the correlation of HTF mass flow in the solar field.

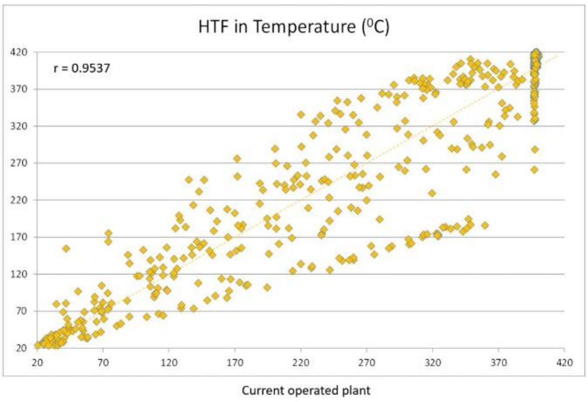

Figure 5. Representation of the correlation of HTF temperature at the inlet of the solar field.

With this result it is possible to conclude that the regression line explains the 97.66% of the total variation observed was about the HTF mass flow and 95.37% of the total variation observed related to the HTF inlet temperature of the solar field.

Short Time Analysis

To improve the applicability of the model of the power plant it its execution time needs to change and adapt to the range of planning for the operation of the plant, whose usual value for this type of production is 72 h. After the execution of the model in the first 72 h, using real plant values in the input to the model, the operation values must update every hour with the corresponding deviations of intermediate vectors (radiation, prices, and thermal management of storage). Then, it is necessary to run the model iteratively in continuous intervals of 72 h, with hourly updates of results and intermediate vectors. This means the scheduled execution of the plant model for 72 h a total of 8760 times throughout the year is required to obtain optimal results of operation in the 72 h following its continuous execution.

The result of the execution of this iterative model will show the optimal strategy for thermal storage in the plant and the auxiliary load heat sources and electricity generation in each hour of operation throughout the year, allowing the plant operator to make appropriate decisions on different power plant control systems.

2.2.3. Economic Parameters

To participate in the electricity market, the PT Plant must bid an hourly sale price of energy to the market, including the capacity production for each hour of the day. The meteorological variables can introduce a stochastic element of variation, which can lead to non-compliance penalties with the energy commitment acquired from the PT Plant [20]. Thermal storage must attenuate these variations for commitment to generation and reduce the influence of meteorological variables that are difficult to predict and control.

The proposed plant model in the present work calculates, by optimization process, the benefits of the programming of electrical energy production, according to the characteristics of the plant.

For the simulation of direct power sales in the electricity market an annual series of values in the price of electrical energy was used. This annual series was created from the arithmetic mean of the 24 series of prices negotiated for each of the hours of the following day in the daily market, expressed in Euros per kilowatt-hour (€/kWh_e), during the period between 1 January and 31 December 2017 (8760 values).

2.2.4. Electricity Generation Optimization Functions

The optimization of the PT plant has been oriented toward the improvement of production through different operation alternatives, considering a plant with thermal storage, as well as an unregulated regime of the electricity market.

For the optimization of the production of electricity, the model of the solar plant with thermal storage using molten salt was analyzed as described. According to the plant architecture it proceeded with its simulation considering its participation in the daily market of electricity. The set of electricity sales results allows us to determine the circumstances that optimize the operation of the plant, improving its economic profit.

The optimization of the system of generation, concentrated solar thermal with thermal storage, uses linear functions and coupling times among the variables. In this approach, it is considered to be a daily change horizon with hourly discretization. To improve the determinist approach, an annual database, corresponding to the real information from the year 2017, is analyzed. energy and electrical aspects are both studied simultaneously, which reflects the reality of the system being considered.

The optimization function presented maximizes the electrical energy generated in the solar plant, parameterized by the electric energy price values in each production hour. Thus, the index of performance (or objective function) is, finally, the economic benefit of the plant activity, subject to a set of equations and inequalities that represent the behavior and the physical limitations (or restrictions) of the system.

The equality restrictions express the equations of the power flow. The restrictions of inequality can be physical (limitations of the capacity of system components), operational (limits of practice of system operation, that must be considered in the model), and of security (determined by a set of contingencies determined by the real-time security analysis) [23].

Next, the formulation of the Thermal Group Hourly Program (TGHP) [23–25] is taken into account in order to study the processes of loading and unloading, at least, a complete cycle of operation. For the formulation of this problem (linear type) the variables used are continuous in the intervals (J) considered.

Solar Field and Thermal Storage System

In reference to the solar field, the relationship between the Direct Normal Irradiation $R_{DNI}(j)$ on the PT collectors and the thermal energy supplied to the thermal storage system and electricity generation system $P_{Solar}(j)$ is shown in Equation (2).

$$(1 - c_{Ct})R_{DNI}(j)A_{Ct} = \frac{1}{3600}\frac{1}{\eta_{Ct}}P_{Solar}(j) \quad \forall j \in J \ , \tag{2}$$

where c_{Ct} represents the losses of the solar field as well as the solar radiation not captured by the collectors; A_{Ct} is the total acquisition surface; and η_{Ct} is the conversion efficiency of solar radiation into heat energy.

For the thermal storage system, the relationship between the thermal energy storage in the molten salt tanks in the hour j, $E_A(j)$, the thermal capacity flow from the solar field collectors, $P_A^-(j)$, and the thermal capacity flow to the power block, $P_A^+(j)$, is shown in Equation (3). Technical restrictions in the thermal storage system, minimum stored thermal energy in the tanks ($E_A^{\min}$), and nominal power in the steam turbine ($P_T^{\max}$), are included in Equations (4)–(7).

$$E_A(j) = E_A(j-1) - \frac{P_A^+(j)}{\eta^+} + \eta^- P_A^-(j) \ \forall j \in J, \tag{3}$$

$$E_A(j) \geq E_A^{\min} \forall j \in J, \tag{4}$$

$$E_A(j) \leq h_{eq} \cdot P_T^{\max} \forall j \in J, \tag{5}$$

$$0 \leq P_A^+(j) \leq P_T^{\max} / \eta_{full\_load} \forall j \in J, \tag{6}$$

$$0 \leq P_A^-(j) \leq P_T^{\max} / \eta_{full\_load} \forall j \in J. \tag{7}$$

Electricity Supply to Power Grid

The power balance of the PT plant is shown in Equation (8), where storage loading and unloading has been independently considered. Thus, the expression includes the two technical storage constraints, thermal capacity flow to the thermal storage system, $P_A^-(j)$, and the thermal capacity flow from the storage tanks, $P_A^+(j)$. The value P_{Spill} represents the power reduction due to the fact that the blur of collectors is very high for radiation periods.

In Equation (8) the solar plant's electric power output is proportional to the amount of energy from the solar field, P_{solar}, at hour j, increased by the capacity obtained from the thermal storage system in the hour j, $P_A^+(j)$, and affected by the efficiency factor η_{sto}.

As described in Equation (2), the electricity generation is also limited by the effects of the thermal storage system and blur of the solar field collectors.

$$\frac{P_T(j)}{\eta_{PB}} = P_{solar}(j) + P_A^+(j)\eta_{sto} - P_A^-(j) - P_{Spill}(j) \quad \forall j \in J \ . \tag{8}$$

The total production variation of the plant is obtained through (9). This value is proportional to the absolute value of the electric power variation generated along two sequential hours [26].

$$\Delta P_T(j) = P_T(j) - P_T(j-1) \forall j \in J, \tag{9}$$

Equations (10) and (11) introduce the variation limits of production (maximum ramps supported) in the production of electricity.

$$\Delta P_T(j) \leq \Delta P^{up} \forall j \in J, \tag{10}$$

$$-\Delta P_T(j) \leq \Delta P^{down} \forall j \in J. \tag{11}$$

Objective Function, Power Limits, and Restrictions

The Objective function represented in Equation (12), expresses the optimum benefit of the total energy production for each hour in the PT Plant, considering the price of the sale in the electricity market (Π_{DM}), as well as the mathematical Equations (8)–(11).

$$\text{Max}\sum_{j \in J}[(\Pi_{DM}(j))P_T(j)]. \tag{12}$$

The objective function is composed by the sales benefit from $P_T(j)$ as a variable parameter of optimization. Equations (13) and (14) show the limits of the PT plant generated power $P_T(j)$.

$$P_T^{\min} \leq P_T(j) \leq P_T^{\max} \quad \forall j \in J, \tag{13}$$

$$\sum_{j \in J} P_T(j) \leq h_{Aeq} \cdot P_T^{\max}. \tag{14}$$

The value $P_T(j)$ is the power of electricity generation of the PT Plant along the entire connection interval. This power is limited by P_T^{Max} as the nominal power of the plant. This limitation influences the amount of energy stored and generated related to the thermal energy obtained through the solar concentrators.

In this work it is considered that, by using the solar multiple defined by the design of the plant, the collection surface is sufficient to obtain the thermal needs of the plant, both in storage and electricity generation.

To obtain the maximum storage capacity of the solar plant an electrical energy amount equivalent to the product of h_{eq} storage hours multiplied by P_T^{Max}, the maximum power of the steam turbine, is required. Under nominal conditions, this term must be increased, according to the turbine's own performance and losses, heat storage efficiency through molten salts, and the plant's self-consumption energy, for the regulation and maintenance of latent heat of recirculation. The formulation of the TGHP by optimization procedures is as shown in Equations (12) and (14).

2.3. Simulation Environment and Model Implementation

For the simulation of the operation through sale, consideration of the hourly prices from the previous year is the better option for comparing the results of this system with the specific remuneration in real markets. Knowing the annual production, as well as the arithmetic average of the price of electricity in the daily market, is necessary for the calculation of profit and remunerations.

For the adjustment value by deviations in the market price calculation it is necessary to consider the arithmetic mean of the hourly values in the price of electricity in the daily market throughout the year of study as the reference price.

As limitations of the considered model, neither the start and stoppage of PT plant generation, nor the dynamics of heating in the solar field, have been modeled. Likewise, the consumption of gas as an auxiliary functional source of heat has been limited attending to the annual operation of its use in the model. Finally, a constant performance in the production of electricity and conversion of radiation has been considered, leaving the inclusion of the functions of temperature for these parameters for future works. The calculations and Case Studies (CS) are shown below, in which the described PT Plant models and the optimization equations have been applied.

The first aim of this storage optimization model is to maximize the economic profit of the production, according to the market price of the electric energy. This will allow an optimal electricity generation forecast to be made in the daily market. The optimization approach has been presented through Equation (11), for sale with daily market price, as an objective function. Equations (3)–(7) are added as constraints. The coefficients η_{Ct}, c_{Ct}, η^+, and η^- have been considered, according to the values shown in Table 1.

Considering either the solar radiation or the selling price of the electricity generated, these parameters are going to set the case studies, establishing the different scenarios for analysis and comparison. Thus, in reference to the available solar resource, the direct normal radiation throughout the year is distributed into two main families. These scenarios have been defined based on current operating values of the PT plant.

The series of results are presented according to the case study of Table 2. In each case, the operation in a 50 MW_e PT plant with thermal storage using double tank of molten salt, with a thermal capacity of 4 equivalent hours of full load production, is considered. The results of the plant operation in this case, as well as the optimal results of operation in absolute values, are represented hereinafter.

Table 2. Defined case studies.

Scenario CS[SR][ME]	Solar Resource Availability [Low DNI; High DNI]	Market of Electricity Behavior [Low price; High price]
CS[LSR][LP]	LSR	LP
CS[LSR][HP]	LSR	HP
CS[HSR][LP]	HSR	LP
CS[HSR][HP]	HSR	HP

DNI: Direct Normal Irradiance, LSR: Low Solar Resource, HSR: High Solar Resource, LP: Low Price, HP: High Price.

Results have been extracted from the full implementation through annual vectors of each entry (8760 values). However, to facilitate the analysis and presentation of results, it is necessary to consider significant intervals of 72 h. These intervals are presented as the most representative ones for the PT plant operation and generation decision-making strategy in the short term.

The first, Low Solar Resource (LSR), corresponds to periods when the radiation received is not sufficient for the production of electrical energy in a continuous manner. Energy storage is a fundamental resource both for the optimization of production and for the maintenance of safety of the solar field temperature (<260 °C). In this stage, the fade out phase, due to excessive solar resources, is not usual. The second family, High Solar Resource (HSR), corresponds to periods when the solar radiation is aimed at production and storage and when the fade out of some collectors of the solar field is frequent, due to excessive solar resources at the plant (>393 °C).

Related to the selling price of the electricity generated in the solar system, there are two periods of classification to determine two forms of operation. The first, High Market Prices (HP), correspond to business days (usually from Monday to Friday) when the high demand for electrical energy raises market values and selling prices, related to the basis of production, availability of different types of plants, and the curve of demand, mainly (65–74 €/MWh_e) [20]. The second period, Low Market Prices (LP), occurs during public holidays or non-working days (mainly Saturdays and Sundays) when the reduction of electric energy demand marks a notable decrease of price in the electricity market (55–65 €/MWh_e) [20].

3. Results

The cases studies analyzed herein consider a solar plant whose size corresponds, in its main characteristics, to the generic plant, with a thermal storage system using a double tank of molten salts with a thermal capacity equivalent to 4 h of full load production. The storage system using a double tank of molten salt is considered to calculate the optimal profit results of the sale of electricity production.

3.1. Optimization of the Daily Operation in Plant

The results of the generation optimization for the proposed system are shown in Figures 6–9. As described in 2.3, this result is obtained according to four selected simulation intervals of 72 h throughout 2017 (from 5–7 July, 17–19 July, 8–10 December, and 27–29 December).

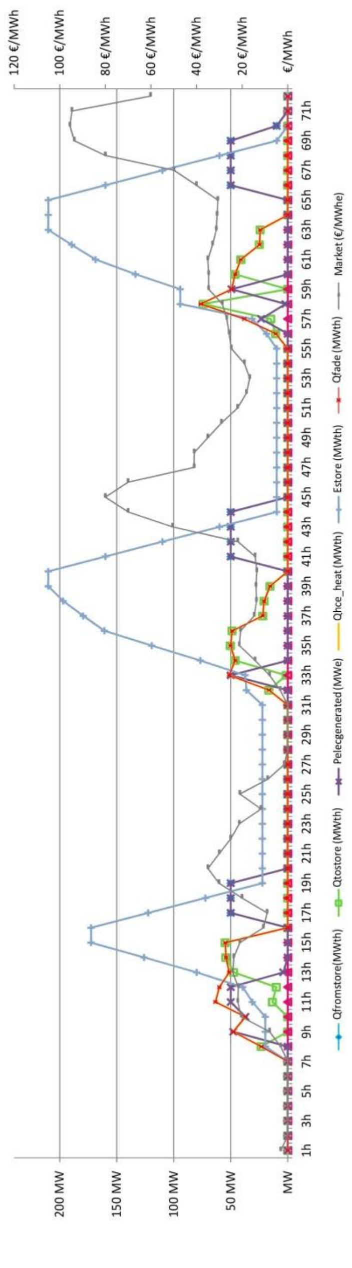

Figure 6. Hourly programming of optimal production CS[LSR][LP].

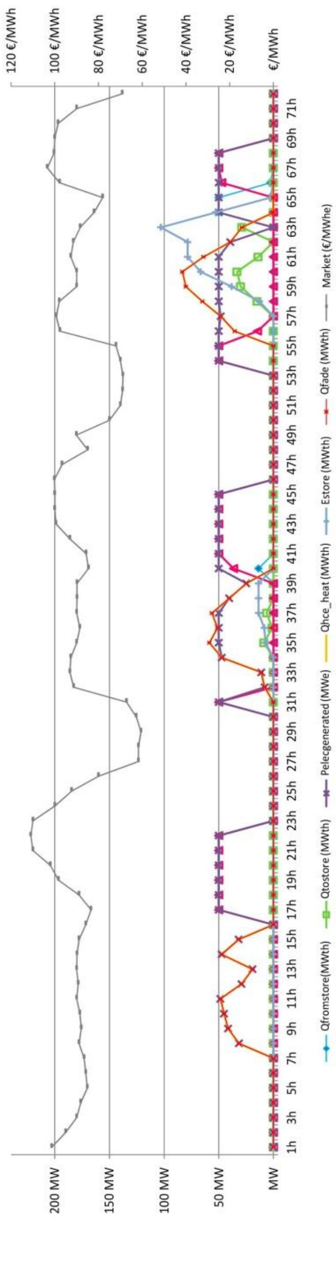

Figure 7. Hourly programming of optimal production CS[LSR][HP].

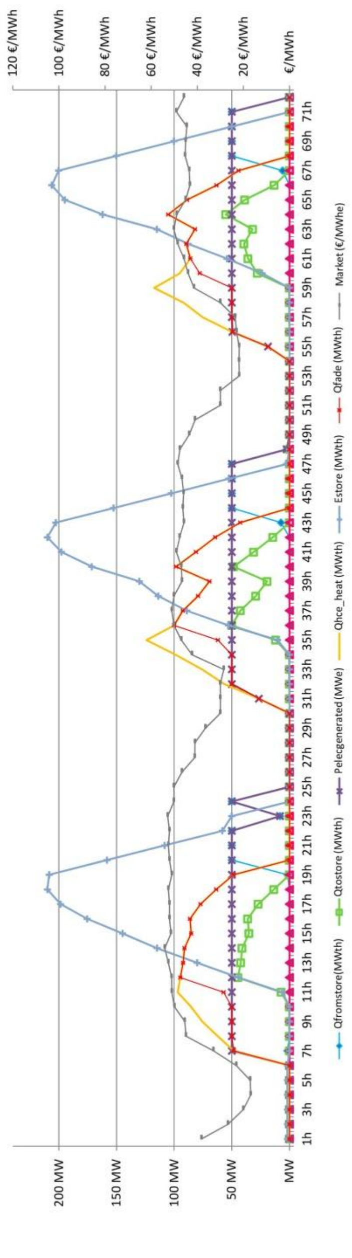

Figure 8. Hourly programming of optimal production CS[HSR][LP].

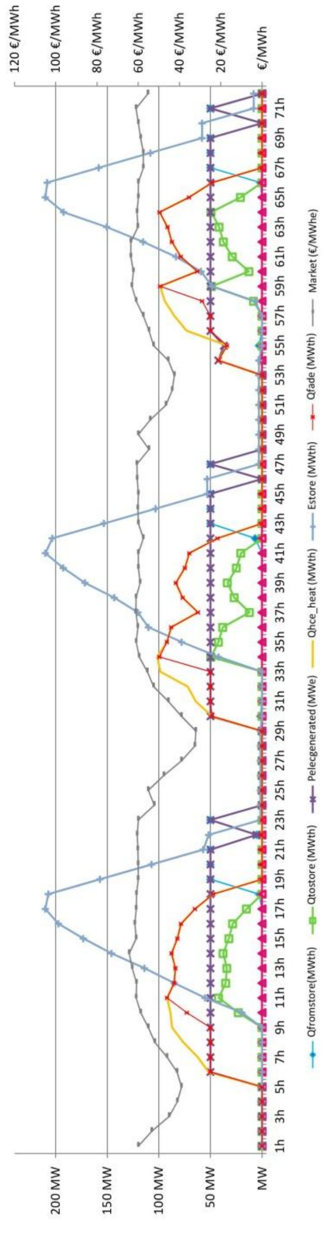

Figure 9. Hourly programming of optimal production CS[HSR][HP].

In Figures 6 and 7, the optimization of operation, solved by the PT solar thermal model plant, can be observed, in which the solar radiation received is used for both the direct generation of electricity through the steam turbine and for the thermal storage as deferred power generation, according to the price changes and tendency of each hour. This storage occurs when the solar radiation received is higher than is necessary for direct generation, considering the gradient of charging for molten salt storage. When the gradient of the thermal storage load is lower than the received solar radiation, the focus system must reduce the thermal solar reception to avoid superheating thermal fluid in the solar field.

When the solar radiation received in the field of collectors is not sufficient to maintain the full load in the steam turbine, the thermal discharge of the deposits of molten salt is an important factor. which depends on the electricity sale price. In a situation of low or zero DNI, the simulated plant model makes use of the discharge gradient of recovery which, in case of being insufficient, is complemented by the use of natural gas support (technically dispensable uses) whenever the rise of the sale price of generated electricity allows it.

In Figures 8 and 9, as in the previous figures, the operation optimization, solved by the model of solar thermal plant and algorithms with linear continuous solution, can be observed, in which the received solar radiation is used for the electricity generation or to operate in the recovery mode and heat storage. In this case, as it occurs in the plant model without storage in summer periods, it can be seen how the simulation model makes the use of natural gas support for electricity generation unnecessary in optimal operation, thus relegating this support to technically essential uses for the solar power plant.

In descending electrical energy prices periods, the solar field begins the recovery phase to raise the temperature of the thermal fluid of the field (recirculation), storing unused solar thermal energy in the double tank of molten salts system. If these descending price periods, usually on weekends, are coincident with a period of high radiation or high temperature gradients, the modeling system will defocus sequential loops of collectors to adapt the radiation received to the electricity production that is required. Table 3 shows a summary of the optimal production results with thermal storage.

Table 3. Summary of results of simulation. Period 72 h with thermal storage.

Scenario	Generated Energy (MWh_e)	Auxiliary Energy Needed (MWh_{th})
CS [LSR][LP]	920.82	0.0
CS [LSR][HP]	2061.31	898.20
CS [HSR][LP]	2716.69	0.0
CS [HSR][HP]	2734.02	0.0

The main complexity in the model solar plant operation is caused by the control of inertia and thermal gradient of each block of the plant (collection, storage, and generation), in order to prevent situations of either overheating or temperature reduction to below safe values in the solar field.

The plant model optimization is evaluated by comparing the results of the 72 h simulation intervals with the vectors from the Equation (8), constrained by Equations (3) to (7). Table 4 shows the comparative results of operation of the 50MW$_e$ PT plant with thermal storage. The result variations due to the optimization process, both from energy production and economic benefit of selling in the market, is expressed by (Δ).

Table 4. Comparative evaluation of optimal operation results in 72 h periods.

Scenario	Generated energy (MWh_e)		
	Direct Algebraical Results	Optimized REsults	Δ
CS [LSR][LP]	873.23	920.82	5.45%
CS [LSR][HP]	1912.69	2061.31	7.77%
CS [HSR][LP]	2505.02	2716.69	8.45%
CS [HSR][HP]	2534.55	2734.02	7.87%

3.2. Economical Results

Table 5 summarizes the operation results of the plant according to the described model and according to the case studies shown in Table 2. In this overview it is possible to see, as a rule, a 50 MW_e PT solar thermal plant, with a thermal storage system, improves the economic benefit derived from its electricity production in a meaningful way (from 5.17% to 7.79%), related to market prices. This storage system manages to operate for a higher number of hours throughout the year and, in the case of reduced availability of solar resource, as shown in CS[LSR][LD], defers to periods in which the price of electricity is highest. Thus, it can be seen that for a similar production, or even a lower one for the second of the scenarios studied, greater economic benefit can be obtained by moving production into hours with more favorable electricity prices. Therefore, the novel strategy shown in this work improves the benefits of energy production for the same solar radiation and TES sizing.

Table 5. Summary of operation results for each study case.

Scenario	Sales Incomings Gross in Spanish Market (€)	Improved Incomings Gross in Spanish Market (€)	Sales Incomings Improvement (%)
CS[LSR][LP]	20373.68	21426.99	5.17%
CS[LSR][HP]	169714.86	181951.30	7.21%
CS[HSR][LP]	84295.88	90862.52	7.79%
CS[HSR][HP]	111104.39	119215.01	7.30%

4. Discussion

In this work, an operation analysis on a currently operating PT solar thermal power plant, with a double tank molten salt energy storage system, is carried out according to the physical parameters of the plant, as well as to a non-regulated electricity market.

The designed model of the PT plant is validated through real data from the different plant systems. This optimized model is applied to 4 case studies, which compare the obtained results with the operational values of the real PT plant. These 4 case studies have been structured in intervals of 72 h, which represent the four possible scenarios of the plant operation related to the availability of the solar resource and the market price of the electricity produced.

Direct algebraical results, shown in Table 4, represent the standard production of the real PT plant, operating since 2014. The results obtained in the optimized operation of the plant allow for improvement of solar resource utilization in periods when the price of the energy produced is more favorable, thus increasing the general operation benefit throughout the year. As a results summary, Table 6 shows the improvement in energy production, according to each scenario.

Table 6. Summary of operation production of electrical energy and incomings for each study case.

Scenario	Generated Energy (MWh_e)	Optimization of Generation (%)	Improved Incomings Gross in Spanish Market (€)	Sales Incomings Improvement (%)
CS[LSR][LP]	920.82	5.45%	21426.99	5.17%
CS[LSR][HP]	2061.31	7.77%	181951.30	7.21%
CS[HSR][LP]	2716.69	8.45%	90862.52	7.79%
CS[HSR][HP]	2734.02	7.87%	119215.01	7.30%

The adaptation of this operation model to another type of plant involves the adaptation of the different parts of the model as well as the input data (solar resource and selling price of electricity). For the solar resource adaptation, either the radiation databases from the town of study or the simulations for their predictions are needed.

To obtain the market prices of electricity, as well as its future estimation, it is necessary to take different tools and platforms, put at the disposal of the production agents by that market operator, into account. According to the European Directives [27], data on electricity sales prices used for this work can be applied to any other installation that participates in these types of markets.

5. Conclusions

This work presents a novel operation strategy for PT plants according to non-regulated electrical markets. A mathematical operation model has been created and calibrated with real values from a currently operated plant. The results obtained in the optimized operation of the plant allow for improvements in solar resource use in periods in which the price of the energy produced is more favorable, thus increasing the general operation benefit throughout the year.

The dynamic parameters of the PT plant are modeled for future studies to improve the results of the operation, as well as to obtain conclusions which allows for optimization of the design of the whole system.

Furthermore, deviations over the expected daily load, which imply penalties applied on the sales of energy production, are under study. The minimization of these deviations is one of the objectives for future research works, due to its influence in the final electricity price and plant benefits.

Author Contributions: J.M.L. and D.B. conceived and designed the mathematical model and its calibration, set up the data acquisition from the currently operating PT power plant, and developed the environment of study and the simulation model; M.R.A. helped with the simulation model and performed the calibration model process; J.M.L. and D.B. analyzed the data; J.M.L. and D.B. wrote the paper.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge the collaboration in this work with the Engineering team of Africana Energía Parabolic Trough solar thermal power plant, located in Cordoba (Spain).

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Solar parameters	
A_{ct}	Real Collection surface for 50 MW solar thermal plant (m^2)
c_{Ct}	Thermal loses coefficient in solar field (%)
$E_A(j)$	Stored energy in period j (MW_{th})
$E_A^{\min}$	Minimum stored thermal energy in tanks (MWh_{th})
$F_{SolarFactor}$	Oversize of solar collection surface referred to the 50MW solar thermal plant without storage (%)
h_{eq}	Equivalent time of production of electricity under full load regime (h)
h_{Aeq}	Equivalent time of operation of the plant in annual period (h)
$N_{MaxHourStorage}$	Maximum stored energy in thermal tanks (equiv. hours of max. production (h))
$P_A^+(j)$	Thermal flow from storage system to power block in period j (MW_{th})
$P_A^-(j)$	Thermal power to storage system in period j (MW_{th})
$P_{Solar}(j)$	Solar power received from the concentrators in the hour j (kW_{th})
$P_{Spill}(j)$	Reduction of radiation by fade out when production peaks occur (kW_{th})
$P_T(j)$	Electrical power generated in steam turbine for the period j (kW_e)
$P_T^{\max}$	Nominal power in steam turbine (kW_e)
$P_T^{\min}$	Min output power in power block (MW_e)
$\Delta P_T(j)$	Gradient of power generation (MW_e)
ΔP^{Up}	Max slope of generation in power plant
ΔP^{DWN}	Maximum slope of thermal discharge or power off
$Q_{HCEHeatMax}$	Nominal thermal energy received from the solar field (kWh_{th})
$Q_{ToStore\_j}$	Thermal energy input to the hot tank in period j (kW_{th})
$Q_{FromStore\_j}$	Thermal energy from the hot tank to the steam turbine in period j (kW_{th})
$Q_{DTurbineGross}$	Nominal thermal energy to the steam turbine (kW_{th})
$Q_{TurbineThermalInput\_j}$	Thermal energy to the steam turbine in period j (kW_{th})
$R_{DNI}(j)$	Direct Normal Radiation as solar resource (kWh_{th}/m^2)
η_{Ct}	Solar thermal efficiency (optical efficiency and loses in pumps and pipes (%)
$\eta_{HEDToSt}$	Storage load efficiency (%)

$\eta_{HEDFromSt}$	Storage unload efficiency (%)
$\eta_{DTurbineGross}$	Thermal-electrical conversion efficiency by design (%)
η_{PB}	Efficiency coefficient in power block (%)
η_{sto}	Coefficient of efficiency of thermal energy storage (%)
Π_{DM}	Price of electricity in Spanish daily market (€/MWh$_e$)
Index	
Ct	Solar thermal field parameters
DM	Daily market
DTurbineGross	Design parameters for steam turbine
DWN	Discharge
HCE	Heat from the solar field
HEDFROMST	Heat from storage system
HEDTOST	Heat to storage system
j	Time, as variable
J	Planning of operating period in hours
Max	Maximum value
Min	Minimum value
Spill	Defocus factor
Up	Charge
Acronyms	
CS	Case Study
CF	Capacity Factor
DIPS	Delayed Intermediate Production System
DNI	Direct Normal Irradiance
HP	High Market Price
HSR	High solar Resource
HTF	Heat Transfer Fluid
LCOE	Levelized cost of energy
LP	Low Market price
LRS	Low Solar Resource
PLP	Peak Load Plant
PT	Parabolic Trough
SM	Solar Multiple
TGHP	Thermal Group Hourly Program

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ARTÍCULO 6

OPTIMIZATION OF 100 MWE PARABOLIC-TROUGH SOLAR-THERMAL POWER PLANTS UNDER REGULATED AND DEREGULATED ELECTRICITY MARKETS CONDITIONS

ENERGIES, 2019, VOL. 12, NO 20, P. 3973. DOI: 10.3390/EN12050935.

Abstract:

Parabolic-trough solar-thermal power-plant investments are subordinate to radiation availability, thermal-energy storage capacity, and dynamic behavior. Their integration into electricity markets is made by minimizing grid-connection costs, thus improving energy-availability and economic-efficiency levels.

In this context, this work analyzes the sizing-investment adequacy of a 100 MW_e parabolic-trough solar-thermal power plant regarding solar resources and thermal energy into power-block availability for both regulated and deregulated electricity markets. For this proposal, the design of a mathematical model for the optimal operation of parabolic-trough power plants with thermal storage by two tanks of molten salt is described. Model calibration is made by using a currently operated plant. Solar-resource availability is studied in three different radiation scenarios.

The levelized cost of electricity and production profit relating to the investment cost are used to analyze plant sustainability. Thus, the levelized cost of electricity shows the best plant configuration for each radiation scenario within a regulated market. For deregulated markets, the optimal plant configuration tends to enhance the solar multiple and thermal-storage capacity thanks to an increment on selling profit. The gross average annual benefit for electricity generation of deregulated against regulated markets exceeds 21% in all radiation areas under study.

Resumen:

La inversión en plantas termosolares parabólica está subordinada a la disponibilidad de radiación solar, la capacidad de almacenamiento de energía térmica y a un comportamiento dinámico. Su integración en los mercados de la electricidad se realiza minimizando los costes de conexión a red, mejorando así los niveles de disponibilidad de energía y eficiencia económica.

En este contexto, este trabajo analiza la adecuación de la inversión en el dimensionamiento de una planta termosolar de colectores cilindro-parabólicos de 100 MW_e en relación con el recurso solar y la disponibilidad de energía térmica hacia el bloque de potencia, tanto para mercado eléctrico regulado como no regulado. Se describe en este trabajo el diseño de un modelo matemático de operación óptima para plantas almacenamiento térmico mediante dos tanques de sales eutécticas. La calibración del modelo se realiza usando una planta real en régimen de operación. La disponibilidad de recurso solar se analiza contemplando tres diferentes escenarios de radiación.

El coste nivelado de la electricidad y los beneficios de producción en relación en los costes de implantación son usados para analizar la viabilidad de la planta. Así, el coste nivelado de la electricidad muestra la mejor configuración de planta dentro de un mercado regulado para cada escenario de radiación. Para mercados no regulados, la configuración óptima de la planta muestra valores mayores de múltiplo solar y capacidad de almacenamiento térmico gracias a un incremento en el beneficio de venta. El beneficio medio bruto anual por generación de electricidad, de mercado no regulado a mercado regulado supera, el 21% en todas las áreas de radiación estudiadas.

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Optimization of 100 MW_e Parabolic-Trough Solar-Thermal Power Plants Under Regulated and Deregulated Electricity Market Conditions

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Received: 14 August 2019; Accepted: 16 October 2019; Published: 18 October 2019

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Abstract: Parabolic-trough solar-thermal power-plant investments are subordinate to radiation availability, thermal-energy storage capacity, and dynamic behavior. Their integration into electricity markets is made by minimizing grid-connection costs, thus improving energy-availability and economic-efficiency levels. In this context, this work analyzes the sizing-investment adequacy of a 100 MW_e parabolic-trough solar-thermal power plant regarding solar resources and thermal energy into power-block availability for both regulated and deregulated electricity markets. For this proposal, the design of a mathematical model for the optimal operation of parabolic-trough power plants with thermal storage by two tanks of molten salt is described. Model calibration is made by using a currently operated plant. Solar-resource availability is studied in three different radiation scenarios. The levelized cost of electricity and production profit relating to the investment cost are used to analyze plant sustainability. Thus, the levelized cost of electricity shows the best plant configuration for each radiation scenario within a regulated market. For deregulated markets, the optimal plant configuration tends to enhance the solar multiple and thermal-storage capacity thanks to an increment on selling profit. The gross average annual benefit for electricity generation of deregulated against regulated markets exceeds 21% in all radiation areas under study.

Keywords: solar thermal; parabolic trough; energy storage; model validation; electricity market; sizing investment; plant optimization

1. Introduction

Research areas in solar radiation, energy storage, and electricity generation (and their control systems even more so) are some the most important technological challenges regarding the exploitation and integration of renewable energy in the electricity market (EM) at the same level as conventional sources [1–3]. Moreover, during the past few years of research European directives, particularly 2009/28/EC (promotion of electricity generated from renewable energy in inner EMs [4]), have reported technicians and departments connected with renewable energies and, more specifically, with solar thermal energy and electricity production. European Union (EU) legislation evolution has followed the dynamics of deregulation that allowed the evolution of installed power capacity on renewable resources in parallel with the development of renewable-resource technologies. This directly depends on technical and legislative factors related to economic support for investment in the construction of this type of power-generation system.

Thus, electricity generation from renewable resources works under regulated market prices, and deregulated market prices with lower and upper limits, established and supported by EU governments, which ensure the economic viability of power plants [5]. In this way, parabolic-trough (PT) solar-thermal power plants, together with the development of thermal-storage systems, allow the increase of electricity generation for solar-thermal systems, and also to make PT plants renewable-energy systems able to meet the requirements of electricity consumption by each hour by.

The technological development of current PT plants set as basic design criteria obtaining sufficient resources to operate the plant for the greatest number of hours possible [6]. The optimization of the solar-field collector area and sizing of the storage system as a whole must be addressed, considering not only the physical factors of location and solar resource, but also strategic factors according to the electricity market, cost of implementation, load curves, and other environmental factors that improve the plant benefits. This analysis facilitates the viable installation of PT plants in lower-radiation locations, allowing distributed electricity generation close to the consumption points in which solar resources may not be high.

From the point of view of electricity generation, PT plants must offer electricity production that is stationary and independent from solar-radiation variability. To do this, the use of a storage system that enables the power block to work continuously is necessary, thus preventing fluctuation risks in direct sunlight. Reliable and efficient thermal storage is a basic condition to introduce thermal systems of electricity production into the market [7]. Thermal-energy storage (TES) by two tanks of molten salt with the same thermal transmission fluid is the most widespread storage technology in PT plants [8].

PT plant optimization regarding location, sizing, operation strategy and EM was studied in the prior literature. In [9,10], PT plants are investigated from a performance and plant operating point of view. Optimization of efficiency by heat loss reduction was carried out. A mathematical programming model to optimize the operation of concentrating solar power (CSP) plants using regenerative Rankine cycle was developed by [11]. Concentrated solar-power plant modelling was presented in [12] based on equations of mass and energy conservation. This model included equivalent TES of 8 h. However, this model did not include electricity sale prices as a decision variable, considering them as constant value. In [13], a 50 MW_e PT plant simulation model was developed from an operating point of view for electricity output prediction. Results were compared to operating plant data. In [14], a solar field TES model for a 50-MW_e solar-only PT plant was presented; the relationship between generated energy and the average lifetime levelized cost of electricity (LCOE) was studied considering regulated EM (REM). In [15], the relationship between generated energy and LCOE was studied in PT plants with two tanks of molten salt TES for the Middle East without considering market prices. This analysis was based on the PT plant model developed in [16]. In addition, other works study PT plants according to the location, Algeria [17], Cyprus (Gr.) [18,19], India [20,21] and Egypt [22]. All of them from an operating point and regardless the type of EM. Guédez et al. [23] presented a technoeconomic analysis of CSP plants with TES and the analysis of its penetration into EM. LCOE assessment was performed and results were compared with an equivalent combined cycle power plant. In [24], an optimization method for CSP plants revenues maximization as a function of electricity prices is presented. This work analyzes the optimal market operation strategy for generic CSP, finding the limitations of Spanish subsidy policies for DEM. In [25], a CSP plant model with thermal storage operating in the context of variable electricity prices was defined. Nevertheless, this work neither studies Deregulated EM (DEM) behavior, nor establishes an optimization PT plants by comparing the results with REM. In [26], a 50 MW_e PT plant operation model with two tanks of molten salt TES and DEM was developed. However, this model did not include the LCOE analysis and neither did DEM-REM operation assessment regarding different solar radiation scenarios.

As shown before, other works analyze PT plants regarding location feasibility. Generic CSP and PT plants are studied by its behavior within variable prices electrical markets. Operation models are as well presented for PT plants, made operation analysis based on LCOE as technoeconomic assessment of the PT plants optimal dimensioning. Nevertheless, previous literature analyzes LCOE considering either REM or does not mention any EM behavior.

According to each location, the sum of DNI provided per square meter is evaluated by 8760 vector values in a yearly period. In this work, not just sunshine was considered, but also cloudy periods along the year for the three representative radiation areas in the modelling process. Likewise, a SM (oversize of solar-collection surface referred to the 100 MW_e solar-thermal plant) range between 1.0 and 2.6 was considered for the implemented mathematical model. On the other hand, solar reception is mainly performed in the infrared spectrum. Thermal exploitation is through an active transmission fluid in medium temperature (from 220 to 400 °C), and concentration by PT concentrating thermosolar systems (CTS). The solidification point of molten salt makes them less useful in solar fields and pipes, making heat-transfer fluid (HTF) by synthetic oil the most common resource.

Categorized according to the way in which they focus sunrays and the technology used to receive the sun's energy [28], PT receivers consist of parallel rows of reflectors curved in one dimension with rotational axis to focus the sunrays. A local controller determines the position for the collector using a shade sensor which determines the sun position at any time, and with the aid of a mathematical algorithm by which the exact position of the sun any time of the year can be known with high precision [14].

The most usual solution for a medium investment cost is the utilization of PT in arrays of more than 100 m long with a curved surface of 5 to 6 m across [32]. Absorber tubes as heat collectors by stainless-steel pipes have a selective coating that is designed to allow pipes to absorb high levels of solar radiation while emitting very little infrared radiation. The pipes are isolated by an evacuated glass envelope. Both reflectors and absorber tubes move following the sun with one degree of freedom. North–South is the preferred collector orientation in the Northern Hemisphere, and East–West in the Southern Hemisphere [33].

2.2. Thermal-Energy Storage: System of Two Molten-Salt Tanks

Combined with an additional thermal-storage system, PT plants allow to divert excess heat to thermal-storage material during the day. Thus, they can continue to produce electricity even when clouds block the sun or after sundown. The mechanical and chemical stability of the system of two tanks of molten salt reduces storage costs by over 65%, and it also increases thermal reversibility compared to other thermal-storage systems [34]. However, the two-tank direct-system TES increases installation complexity and therefore its implementation costs. The whole efficiency of this double thermal-exchange system, synthetic oil in the solar field, molten-salt TES, and steam in the power block, is lower than a single thermal-exchange system with synthetic oil in the solar field and steam in the power block.

Nevertheless, data relating to investment returns regarding the implementation and maintenance costs of the solar field are directly related to the use of TES [8]. The low uniformity of solar capture of the field, due to different parameters and meteorology, makes the use of partial blurs by collectors necessary that increase the transient effect of solar collection, hindering plant operation [35]. Thus, TES systems offer the possibility to provide reliable electricity that can be dispatched to the grid when needed, including after sunset to match late-evening peak demands, or even around the clock to meet base-load demands [28,36]. Thus, TES availability optimizes reception surface and dynamizes plant operation enhancing the economic benefits of electricity generation. The schema in Figure 1 shows the PT plant implementation with two-tank direct-system TES [26].

The novelty of this work lies in the plant investment viability comparison between operation sales benefits and investment cost, according to regulated and deregulated EM for a 100 MW_e PT plant. The electricity-production and LCOE evolution values with SM and TES are as well studied. As added value, the optimal dimensioning of the PT plant regarding the markets operation and LCOE analysis is compared in each of the radiation scenarios. Results show how accurate is LCOE analysis for the optimal dimensioning of the PT plant for both regulated and deregulated EM. Hence, LCOE shows accurate analysis in REM, whereas DEM allows for greater plant sizing and enhances the benefits. Average DEM's benefits exceed REM's by 21%, it is therefore essential to consider the type of EM to perform an optimal feasibility analysis of this type of plants.

Therefore, the main objectives of this work are first to establish optimal solar-plant sizing according to solar-resource availability, the size of the solar field, and thermal-storage capacity for a 100 MW_e PT plant. Second, to analyze the evolution of electricity generation and the LCOE as a function of solar multiple (SM) and TES. Third, to establish the relationship between solar-field oversize and TES capacity needed to fit electricity market (EM) demands, which enhance plant benefits under regulated- and deregulated-electricity-market requirements. For REM, the LCOE is one of the main tools to analyze optimal plant sizing. Nevertheless, in DEM factors such as electricity demand, market price and selling strategy must be considered for plant-investment optimization.

2. Materials and Methods

2.1. Location of Direct Normal Irradiance (DNI) and Solar Field

Solar radiation as the main source of energy in solar-thermal power-generation plants considers its thermal properties related to spectral wavelength (infrared and visible spectrum as 93% of transport energy) [27]. Regarding PT plants, the specific location allows one to calculate the main solar parameters (specified in surface units) as annual DNI (MWh/year), real incidence angle, thermal energy from the solar field (MWh/year), thermal-efficiency peak (%), as well as total hours of plant full load and annual CO_2 emission reduction related to a standard coal plant (kg/year) [28,29].

To identify the solar resources required in electricity production using PT plants, it is necessary to characterize the parameters of solar radiation according to definitions and equations that allow quantification of the obtained resources. They start from definitions and parameters studied in [30] that in-depth analyze the received solar energy and the mathematical relationships between the physical parameters dependent on this radiation.

After the definition of the different generic radiation values, the next step is to particularize these to the specific location of Earth's surface that circumscribes this study. In [31], it was assumed that solar-concentration systems are economically viable for locations with annual solar isolation greater than 1800 kWh_{th}/m^2/year. The forecast of solar radiation, gathered in monthly periods, is obtained from the DNI and cloudy log values used as envelop curves. Obtained curves are used as input parameters in solar-plant modelling to decide the best plant operation. To achieve such a goal, this work presents the classification of solar-radiation surfaces considering three intervals for the study (low radiation; medium radiation; high radiation), as shown in Table 1. This classification is related to three types of PT plant investment viability, considering technoeconomic and EM assessments.

Table 1. Representative considered Direct Normal Irradiance (DNI) investment scenarios.

Location	Vittoria (Italy)	Posadas (Spain)	Death Valley, CA (USA)
DNI Scenarios	Low radiation (Area 1)	Medium radiation (Area 2)	High radiation (Area 3)
Daily average DNI	5 KWh_{th}/m^2	6 KWh_{th}/m^2	7 KWh_{th}/m^2
Coordinates	36°57′N, 14°31′E	37°45′N 5°3′W	36°14′N 116°49′W
Average temperature	16.73 °C	21.10 °C	25.10 °C
Elevation	168 m	88 m	92 m

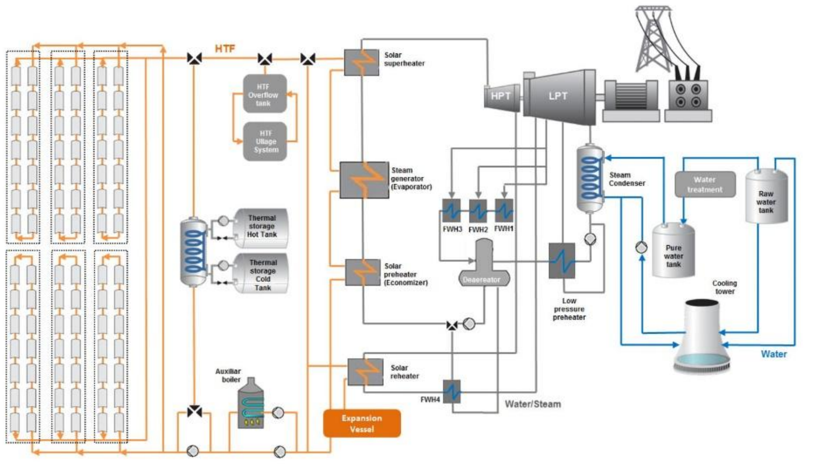


Figure 1. Parabolic trough (PT) solar-thermal power-plant implementation [26].

2.3. PT Plant Managment and Implementation

2.3.1. Plant-Management Analysis

PT plants with TES systems in commercial operation rely on HTF as the fluid that transfers heat from collector pipes to heat exchangers where water is preheated, evaporated, and then superheated. The superheated steam runs a turbine that drives a generator to produce electricity. After being cooled and condensed, water returns to the heat exchangers. In the water-condenser process, the water-cooler heat exchanger is the most common system, but it is unusual for PT plants in desert environments, where a dry-cooler is a must.

There are four main configurations of thermal storage in PT plants depending on the amount and availability of solar radiation, load-out needs, and hourly sun distribution. The intermediate load configuration (ILC) was designed to produce electricity when the available sunshine is sufficient to supply thermal energy during specific need periods. It requires only a small amount of thermal storage and the smallest investment cost. The delayed intermediate production system (DIPS) collects solar energy throughout the day, but produces electricity from noon to sunset according to the highest electricity needs. It requires a large amount of storage. The Based load configuration (BLC) runs for twenty-four hours per day during most of the year. It needs a larger amount of thermal storage and it is appropriate when power-generation limits are specified that are lower than the real capacity of the solar-thermal plant. The peak load plant (PLP) was designed to only provide electricity for a few hours considering higher load daily levels. It requires a large turbine and a large amount of storage to produce the most expensive but also most valuable electricity [28].

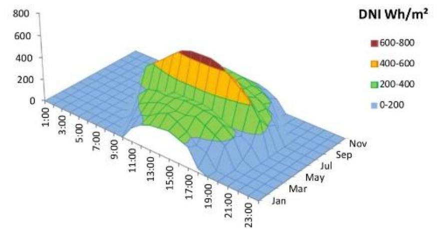
Regarding solar resources, there are two main operation modes of the system. In generation and storage mode, high solar resource (HSR), solar radiation is sufficient to give enough energy to the steam turbine to operate at full capacity. Leftover heat can be stored in the two-tank system by using molten salt. In generation and recuperation mode, low solar resource (LSR), the storage system adds thermal energy to the system to allow full capacity in the steam turbine when solar radiation is null or not enough.

As shown in Figure 1, the presented PT plant was equipped with backup power from fossil fuels. Auxiliary gas-heat contribution is given by higher heating value (HHV) natural-gas combustion in the boiler, producing complementary heat that, with appropriate mixing valves, increases the HTF temperature to suitable values focused to operate in secure intervals. Its main use is based on the first startup operation of any day as well as for covering the solar radiation fluctuations along the day [26].

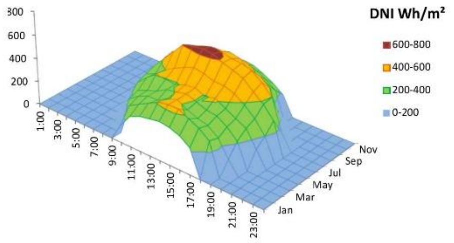
Relating to the EM selling price, this work includes two different scenarios. In REM, fixed price of electricity are considered in the plant operation. For DEM, two plant-operation classification periods are considered. High market Prices (HP) correspond to high demand of electrical energy, and low market price (LP) where electricity demand decreases with market prices [26].

2.3.2. Implementation Basics

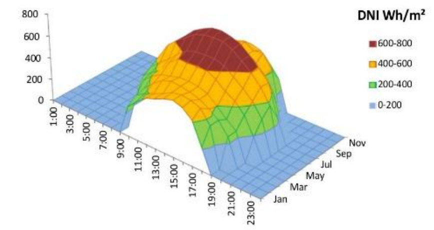
In this work, a perfect solar forecast was assumed with the DNI involved curves shown in Figure 2. Sunshine and cloudy periods during the year were also considered for the three representative locations around the world: Vittoria (Italy), 36°57′N 14°31′E; Posadas (Spain) 37°45′N 5°3′W; and Death Valley, CA (USA), 36°14′N 116°49′W. For specific formulation, real solar radiation in hourly distribution for the year 2017 [28,37] was considered here.



(a)



(b)



(c)

Figure 2. Average curves from yearly DNI. (**a**) Vittoria (Italy); (**b**) Posadas (Spain); (**c**) Death Valley, CA (USA).

Regarding PT plant configuration, Table 2 shows a summary of the main design parameters [38] based on the scheme of the solar PT power plant with two tanks of molten-salt TES from Figure 1. The information there was used to configure the mathematical model proposed for the plant. These parameters vary among plants, taking into account the SM in the solar field and TES size by equivalent hours of electricity generation [1,36].

Table 2. Reference design values for 50MW$_e$ PT plant with two-tank molten-salt thermal energy storage (TES) [38–40].

Solar Field		
PT collectors	Units	624
Total collector surface	m^2	475,438
Solar-thermal efficiency $\eta_{Ct}(\eta_{Solar})$	%	51.6
Solar-field losses c_{Ct}	%	<1
Average operation temperatures	°C	260–391
Solar-field input temperature	°C	293
Solar-field output temperature	°C	391
Pressure in checkpoints		
Thermal-fluid-pump output	bar	15.30
Solar-field input	bar	14–28
Solar-field output	bar	10–15
Steam-generation system input/output	bar	391/293
Molten-salt exchange input/output	bar	293–380
Yearly received thermal energy	MWh$_{th}$	1,090,000
Total thermal energy collected by heat-transfer fluid (HTF) system	MWh$_{th}$	465,000
Collector thermal efficiency	%	43
Total average efficiency	%	16
Thermal energy storage (Seven equivalent hours of thermal storage)		
Composition of thermal fluid		60% NaNO, 40% KNO
Initial operation point	°C	221
Molten-salt mass	T	20,000
Molten-salt global flux	Kg/s	948
Low-temperature tank	°C	292
High-temperature tank	°C	391
Total storage capacity	MWh$_{th}$	1010
Storage efficiency $\eta^{+}(\eta_{HEDFromSt})$	%	98
Storage-recovery efficiency $\eta^{-}(\eta_{HEDToSt})$	%	97
Steam turbine. Single recirculation, four steam extractions		
Nominal electric power	MW$_e$	49.9
Residual loses	MW$_e$	5.0
Efficiency ($\eta_{DTurbineGross}$)	%	99
Net energy production	MWh$_e$	160,000
Input steam to turbine	bar	100 (370 °C)
Recirculation	bar	16.5 (370 °C)
Steam nominal flux	kg/s	59

2.4. Mathematical Modelling and Simulation Process

For the mathematical modelling and simulation process, plant management and operation, as well as a detailed study of the elements to be introduced in the model design, have been considered. EM parameters were analyzed to obtain operation limitations to adapt this model to network needs. [26]. Thus, data for market prices and electricity generation allow to validate the presented PT plant-operation model. Economic information and solar-radiation data correspond to the year 2017 [37].

2.4.1. PT Solar-Thermal Plant Modeling

This study uses plant modeling based on a currently operated PT plant with 50 MW_e net output. Seventy-six loops of solar collectors plus 12 modules in each loop are necessary for such a plant. Considering high-efficiency solar collectors, the surface interval needed for this plant is from SM = 1.0 to 2.1 to obtain better production in different radiance periods. Real solar-radiation values were used to obtain numerical results.

HTF temperature tends to be a fixed value along the plant operation in order to get the maximum efficiency. HTF fluid pressure keeps constant, expansion tanks maintain the fluid pressure within the solar field loops, helping to balance the system. Therefore, the plant makes continuous adjustments on the HTF fluid flow, trying to get the optimal fluid conditions at the power block input [14]. Thus, HTF nominal and minimum working temperatures are set to 391 °C and 380 °C respectively in the PT plant model. When the HTF temperature is below 380 °C, according to the operation strategy the plant demands thermal energy from the TES system or switches to standby mode.

The two-tank direct storage system, 1 through 7 h of equivalent full load thermal energy, was produced with 305.76 to 1348.40 MWh_{th}, and 391 °C fluid temperature [1,41].

The power block is formed by a regenerative Rankine cycle with superheating, reheating and regeneration, used for the electrical power generation. The working temperature of the oil directly influences the conception and design of the steam generation block. Temperatures below 400 °C limit the average conversion efficiency of the thermodynamic cycle, coming down to 37% [40]. 391 °C is the nominal inlet temperature, 293 °C the outlet temperature, 100 bar the boiler operating pressure, and 20% thermal power fraction for standby or startup.

The average efficiency intervals are shown in Table 3 from a generic 50 MW_e power plant [39]. These values were used for the analyzed plant in these simulations.

Table 3. 50 MW_e PT plant accumulative efficiency coefficients. Empirical averages [39].

DNI	η_S	η_{HED-TS}	η_{HED-FS}	η_{DTG}
100.0%	65.0%	97.5%	98.0%	99.0%

The PT plant model was designed by using the THERMOLIB© library [42]. Considered design parameters were location area, plant modeling, DEM, REM, and economical valuation, including plant benefits regarding the type of EM and costs. The structure of the proposed PT plant model was created in MATLAB© (2016b, MathWorks, Cambridge, UK) [43] in accordance with its architecture and operation mode. The simulation environment structure, detailed input, and output data flow are shown in Figure 3 [26].

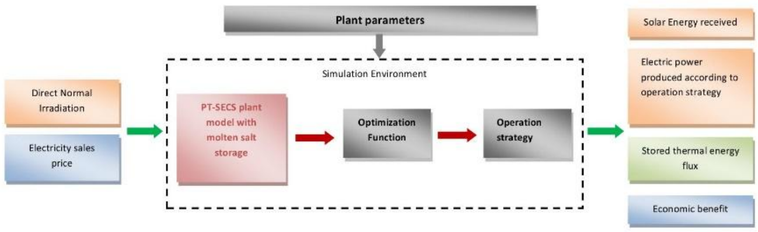


Figure 3. Simulation environment and data flow [26].

The plant operation algorithm defines the thermal energy sent to the power block, the thermal energy to storage into the molten salt tanks, or a combination of both direct discharge and thermal storage. The gross electric energy generated is affected by the power block and the electric generator technical characteristics. Finally, net electricity generation is the gross energy production subtracted by the generation efficiency. The functional unit for a power block and the net electricity generation model is shown in Figure 4 [14].

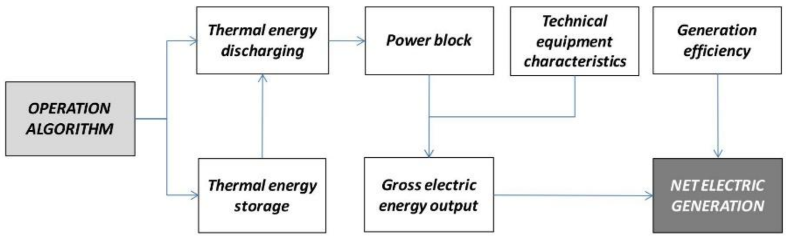


Figure 4. Functional unit for power block and net electric energy output models [14].

2.4.2. Implementation of the Model into Real PT Plant

The solution of the mathematical optimization problem was formulated by linear programming using the MATLAB© [43] "linprog" solver. Hourly updates of corrections are introduced in the model matrix of vectors due to deviations in final solar radiation, final prices of market, energy accounting in the storage system, and electric power finally produced. The proposed model uses parameters of positive real values formed by vectors of 8760 elements of real numbers. The optimization model used variables are solar resource, R_{DNI}, solar multiple, F_S, TES, N_H, thermal energy from storage, Q_{FS}, thermal energy to storage, Q_{TS}, fadeout, Q_{HCE-F}, and price of electricity in DEM, Π_{DM}, formed by vectors of 8760 elements of real numbers [26]. The results of production were obtained over four vectors of 8760 values, the electricity power generated, P_{E_j}, using a predictive model, the electricity price on REM, Π_{RM_j}, and DEM, $[\Pi_{HMP\_j};\Pi_{LMP\_j}]$ through historical values. Π_{HMP_j} and Π_{LMP_j} correspond to high/low price of electricity into DEM.

PT Plant Model Calibration

Model calibration by using data from a currently operated PT plant validates the used tools. In the calibration process, validation of the model is made by comparison of the behavior of two of its main parameters in both model data results and those from the real system of the plant. They were the mass flow of synthetic oil at the exit of the pressure group in the solar field, and the fluid temperature at the same point. The use of these values is determined by their significance in plant operation.

For this calibration, real physical parameters from the "La Africana Energía" 50 MW_e PT solar-thermal power plant located in Posadas (Spain) 37°45′N 5°3′W were used. After completing this calibration process, validation results made it possible to determine whether the proposed model could anticipate the behavior of the real system in a reliable way. For management of thermal resources, this plant had two tanks of molten salt with 7 h of equivalent TES.

Correspondence between real plant data and the obtained values from the implemented model was made by using the coefficient of determination (R^2), which indicates the percentage of values that meet with the correlation between the data of the plant and the model. As detailed in [26], a validation study explains up to 97.66% and 95.37% of the total variation observed in HTF mass flow and inlet temperature respectively.

Short Time Analysis

In this work, the PT plant could take advantage of both sale options under regulated or deregulated market prices. In this way, the optimization model calculated the benefits on the electrical-energy production schedule according to the chosen market. The study period was daily throughout a calendar year. For REM, the selling price of electricity is structured in bands of fixed amplitude, established by the managing entity of the electricity market in each state. In order to simulate the sale of electricity in DEM, an annual series of values of the price of electrical energy was used. This annual series was created from the arithmetic average of 24-hour price series that are negotiated for each hour of the following day in an EM (€/kWh$_e$). The period considered was 1 January to 31 December 2017, with a total of 8760 entries [26].

The yearly series of results were distributed into two main families, solar resource and generated-electricity selling price, where case studies defined were set as shown in Table 4. Figure 5 plots 72 h scheduling of optimal production for the High Solar Resource (HSR) and Low Price (LP) case studies into DEM [26].

Table 4. Defined case studies for deregulated and regulated markets sale of electricity. Note: FP, Fix-Price; LP, Low Price; HP, High Price; HSR, High Solar Resource; LSR, Low Solar Resource.

Scenario	Solar Resource Availability	Deregulated Market Behavior	Reregulated Market Behavior
CS[LSR][LP;FP]	LSR	LP	FP
CS[LSR][HP;FP]	LSR	HP	FP
CS[HSR][LP;FP]	HSR	LP	FP
CS[HSR][HP;FP]	HSR	HP	FP

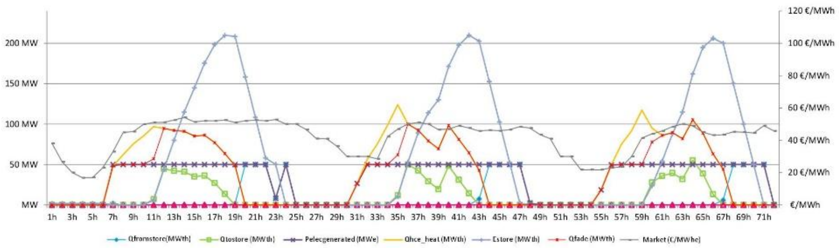


Figure 5. Hourly programming of optimal production CS[HSR][LP] [26].

2.4.3. Optimization Problems

The optimization of the PT plant has been oriented toward the improvement of production of electricity in both regulated and deregulated daily markets. Thus, the index of performance (or objective function) is the economic benefit of the plant activity, subject to a set of equations and inequalities that represent the behavior and the physical restrictions of the system.

The equality restrictions express the equations of the power flow. The restrictions of inequality can be physical (limitations of the capacity of system components), operational (limits of practice of system operation, that must be considered in the model), and of security (determined by a set of contingencies determined by the real-time security analysis) [3]. Next, the formulation of the thermal group hourly program (TGHP) [3] is taken into account in order to study the processes of loading and unloading, at least, a complete cycle of operation. For the formulation of this problem, linear programming in the intervals (J) was considered.

Optimization Problems for Electricity Sales Benefits

A generic optimization problem is expressed in Equation (1), where $\Pi_{\_j}$ represents a generic price of electricity sale in the period j, and x_i, the decision variables. Likewise, the objective function dependence on x_i, the decision variables, is as well declared. Equation (2) expresses the electricity production, P_{E_j}, as a function of the decision variables, x_i, in the period j. Thus, the Optimization problems are set for DEM in Equations (3) and (8), and for REM in Equation (10). These equations express the optimum benefit of the total electricity production for each hour in the PT Plant, considering the price of electricity sale in both DEM, $[\Pi_{HMP\_j};\Pi_{LMP\_j}]$ and REM, Π_{RM_j}. In each equation, the optimization problems are composed by the sales benefit from P_{E_j}, as parameter of optimization. Constraints for Π_{HMP_j}, Π_{LMP_j}, and Π_{RM_j}, are expressed in Equations (4), (9) and (11) respectively. Equations (5) and (6) give the limits for generated power by the power block. The power generated is limited by P_{DE} and P_E^{min} as the nominal and minimum power generated of the plant. This limitation influences the amount of energy stored and generated related to the thermal energy obtained through the solar concentrators. To obtain the maximum electricity power generated of the PT plant, an electrical energy amount equivalent to the product of N_{AH} storage hours multiplied by P_{DE}, the nominal power of the steam turbine, is required. In Equation (7), the number of decision variables together with their constraints $(a_i - b_i)$, are represented. Considered decision variables for the electricity power generated are F_S and N_H. Constraints for the defined cases of studies are between the intervals [1.0:0.1:2.6] and [0:1:7], for F_S and N_H respectively:

$$\max_{x_i \in X} \sum_{j=1}^{n} \left[\left(\Pi_{\_j} \cdot f(x_i)_{\_j} \right) \right] \tag{1}$$

$$P_{E\_j} = f(x_i)_{\_j} \quad \forall j \in J \tag{2}$$

$$\max_{x_i \in X} \sum_{j=1}^{8760} \left[\left(\Pi_{HMP\_j} \cdot P_{E\_j} \right) \right] \tag{3}$$

$$\text{s.t.} \quad 0 \le \Pi_{HMP\_j} \quad \forall j \in J \tag{4}$$

$$P_E^{min} \le P_{E\_j} \le P_{DE} \quad \forall j \in J \tag{5}$$

$$\sum_{j=1}^{8760} P_{E\_j} \le N_{AH} \cdot P_{DE} \quad \forall j \in J \tag{6}$$

$$a_i \le x_i \le b_i \quad for\ i = 1\ to\ 2 \tag{7}$$

$$\max_{x_i \in X} \sum_{j=1}^{8760} \left[\left(\Pi_{LMP\_j} \cdot P_{E\_j} \right) \right] \tag{8}$$

$$\text{s.t.} \quad 0 \le \Pi_{LMP_j} \quad \forall j \in J \tag{9}$$

$$P_E^{min} \le P_{E\_j} \le P_{DE} \quad \forall j \in J$$

$$\sum_{j=1}^{8760} P_{E\_j} \le N_{AH} \cdot P_{DE} \quad \forall j \in J$$

$$a_i \le x_i \le b_i \quad for\ i = 1\ to\ 2$$

$$\max_{x_i \in X} \sum_{j=1}^{8760} \left[\left(\Pi_{RM\_j} \cdot P_{E\_j} \right) \right] \tag{10}$$

$$\text{s.t.} \quad 0 \le \Pi_{RM\_j} \le \Pi_{RM}^{max} \quad \forall j \in J \tag{11}$$

$$P_E^{min} \le P_{E\_j} \le P_{DE} \quad \forall j \in J$$

$$\sum_{j=1}^{8760} P_{E\_j} \le N_{AH} \cdot P_{DE} \quad \forall j \in J$$

$$a_i \le x_i \le b_i \quad for\ i = 1\ to\ 2$$

Objective Function for Electricity Production

In Equation (12), a generic Objective function is represented. The electricity production, P_{E_j}, as a function of x_i, is expressed in Equation (2) for the period j. Hence, Equations (13) gives the Objective function of electricity production. Likewise, constraints are defined in Equations (5)–(7). Restrictions for F_S and N_H are between the respective intervals [1.0:0.1:2.6] and [0:1:7]:

$$\max_{x_i \in X} \sum_{j=1}^{n} \left[\left(f(x_i)_{\_j} \right) \right] \tag{12}$$

$$P_{E\_j} = f(x_i)_{\_j} \quad \forall j \in J$$

$$\max_{x_i \in X} \sum_{j=1}^{8760} \left[\left(P_{E\_j} \right) \right] \tag{13}$$

$$\text{s.t.} \quad P_E^{min} \leq P_{E\_j} \leq P_{DE} \quad \forall j \in J$$

$$\sum_{j=1}^{8760} P_{E\_j} \leq N_{AH} \cdot P_{DE} \quad \forall j \in J$$

$$a_i \leq x_i \leq b_i \quad for\ i = 1\ to\ 2$$

Equations (14) and (15) give the conversion relationship between thermal energy and electricity production, considering the efficiency factors in each step of the process:

$$\eta_{DTG} \cdot Q_{DTG} = P_{DE} \tag{14}$$

$$\eta_{DTG} \cdot Q_{TTI\_j} = P_{E\_j} \quad \forall j \in J \tag{15}$$

The thermal storage system was sized to allow the power block to operate at its maximum load, Q_{DTG}, using energy from storage alone with the same thermal energy for charging and discharging (Q_{FS} and Q_{TS}). The addition of a thermal source provides additional energy for electricity generation, Q_{TTI_j}, increasing capacity and ancillary services. We assumed that hourly energy losses in thermal storage were 0.03% [39].

Solar Field and Two Tanks of Molten Salt Thermal Storage

Relating to the solar field, the relationship between the Direct Normal Irradiation R_{DNI} on the PT collectors and the thermal energy supplied to the thermal storage and electricity generation systems is shown in Equation (16):

$$\frac{Q_{HCE-H\_j}}{\eta_S} = (1 - C_{Ct}) \cdot R_{DNI} \cdot A_E \cdot F_S \quad \forall j \in J \tag{16}$$

where Q_{HCE-H_j} is the thermal energy received from solar concentrators in hour j as a known value. η_S is solar-thermal conversion efficiency as a factor of optical efficiency and heat losses in pumps and pipes, C_{Ct} represents the losses of the solar field as well as the solar radiation not captured by the collectors, and A_E is the total acquisition surface. In this equation 174,000 m^2 is the value of reference for A_E in 100 MW_e solar thermal plants [39].

For the storage system, to obtain the optimized equation of the electricity power generated in the hour j, P_{E_j}, first basic analysis considered a maximum fixed capacity for TES, given by the total number of hours of generation over a one-day cycle in while solar radiation is not enough to supply thermal needs. The relationship between storage energy and time of generation from storage is given in Equation (17), where E_{S_j} is the thermal energy storage in the molten salt tanks in the hour j, for each period of 24 h throughout the year, and Q_{DNI} as the maximum solar field direct normal irradiance received. As Q_{DNI} is dependent on the value of SM, to run the plant model in intervals of 24 h, a total of 8760 times throughout the year is necessary to fix maximum TES:

$$N_H = \frac{\sum_{j=1}^{24}\left(E_{S\_j}\right)}{Q_{DNI}} \quad \forall j \in J \tag{17}$$

In Equation (18), the relationship between E_{S_j}, the thermal energy flow from the solar field collectors, Q_{TS}, and the thermal energy flow to the power block, Q_{FS}, is shown. Technical restrictions in the thermal storage system, minimum stored thermal energy in the tanks, E_S^{min}, nominal power in the steam turbine, P_{DE}, thermal–electrical conversion factor, η_{DTG}, as well as η_{HED-TS} and η_{HED-FS} storage load/unload factors [39], are included in Equations (19)–(22):

$$E_{S\_j} = E_S(j-1) - \frac{Q_{FS}}{\eta_{HED-FS}} + Q_{TS} \cdot \eta_{HED-TS} \quad j \in J \tag{18}$$

$$E_{S\_j} \geq E_S^{min} \quad \forall j \in J \tag{19}$$

$$E_{S\_j} \leq N_H \cdot P_{DE} \quad \forall j \in J \tag{20}$$

$$0 \leq Q_{FS} \leq \frac{P_{DE}}{\eta_{DTG}} \tag{21}$$

$$0 \leq Q_{TS} \leq \frac{P_{DE}}{\eta_{DTG}} \tag{22}$$

Electric Power Supply

The power balance of the PT plant is shown in Equation (23), where storage loading and unloading has been independently considered. The electric power output, P_{E_j}, is affected by Thermal–electrical conversion factor, η_{DTG}, and proportional to the amount of energy from the solar field, Q_{HCE-H_j}, the thermal flow to the thermal storage system, Q_{TS}, the thermal flow from the storage tanks, Q_{FS}, and the fadeout of solar collectors when thermal production peaks occur, Q_{HCE-F}, and affected by the efficiency factor η_{HED-FS}.

$$\left(\frac{P_{E\_j}}{\eta_{DTG}}\right) = Q_{HCE-H\_j} + \eta_{HED-FS} \cdot Q_{FS} - Q_{TS} - Q_{HCE-F} \quad \forall j \in J \tag{23}$$

2.4.4. Simulation Environment and Implementation Process

The two market configurations considering three specific locations are compared here. This kind of study allowed authors to include SM and TES as decision variables for the optimization model. To allow the comparison of results and optimizations regarding the EM for the three main radiation scenarios from Table 1, the net installed electricity capacity at any of the locations was set at 100 MW$_e$. It was formed by two twin plants of 50 MW$_e$ each. Thereby, it was possible to define similar conditions of the turbine and power block in each configuration. The results show the optimal solution for SM, TES and electricity sales benefits. SM was considered between the [1.0:0.1:2.6] interval and thermal storage between the [0:1:7] interval. Table 5 shows a summary of the analyzed different variables, including their scope, for each specific location and EM.

Table 5. Defined cases studies for optimal plant investment. Note: REM, Regulated Electricity Market; DEM, Deregulated Electricity Market.

Name	Electricity Market	Thermal St. (Equivalent Hours)	Solar Multiple
Area 1 [EM][TES][SM]	[REM;DEM]	[0:1:7]	[1.0:0.1:2.6]
Area 2 [EM] [TES][SM]	[REM;DEM]	[0:1:7]	[1.0:0.1:2.6]
Area 3 [EM] [TES][SM]	[REM;DEM]	[0:1:7]	[1.0:0.1:2.6]

3. Results

Considering the three radiation intervals around the world as described in the previous sections and study cases defined in Table 5, results in this paper are focused on three main blocks. The first deals with sizing optimization of the PT plant. The second is technoeconomic analysis of the plant operation. Finally, the third block focuses on plant investment viability by the comparison between operation sales benefits vs. investment cost according to regulated and deregulated EM.

3.1. Plant Sizing-Optimization Scenarios

The optimization model offers a set of optimal values for produced energy and equivalent hours of operation. Figures 6–8 show the optimization results for each area of considered radiation. In each figure, the points that define the optimal strategy of TES and SM, adjusted to the lowest cost of investment of the plant and the highest production, are represented.

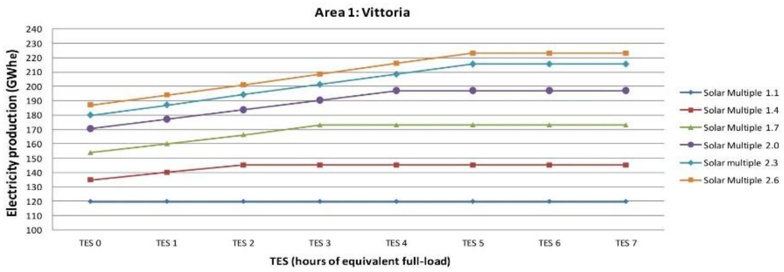


Figure 6. Optimal energy production with SM and TES for Area 1 (Vittoria).

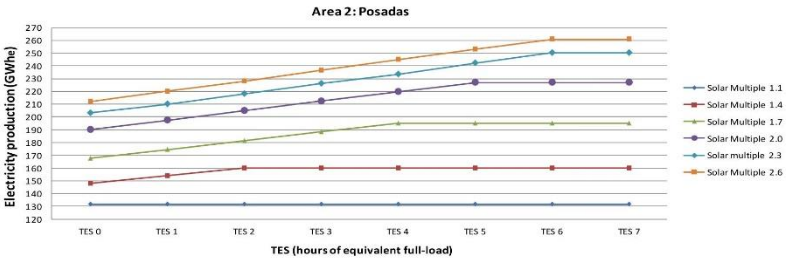


Figure 7. Optimal energy production with SM and TES for Area 2 (Posadas).

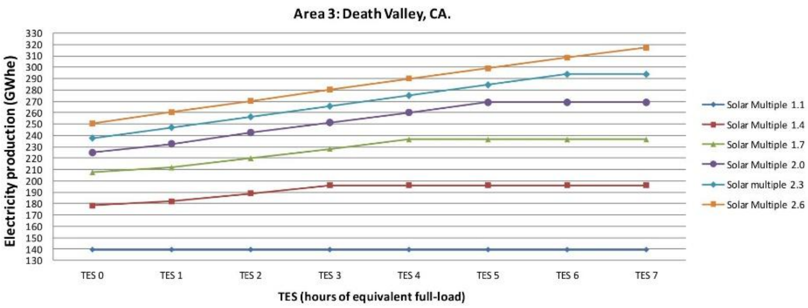


Figure 8. Optimal energy production with SM and TES for Area 3 (Death Valley, CA).

Figure 6 indicates the optimal sizing for a solar-thermal plant in this area, with an SM of 2.6 and an equivalent thermal storage of 5 h. More storage does not imply greater total annual production. In Figure 7, it can be observed that the peak of production was at 6 h equivalent of thermal storage and an oversize of the solar field of 260%. In Figure 8, it can be seen that the point of optimal electricity production was established with an oversized plant in 260% and 7 h equivalent of thermal storage. Table 6 summarizes the optimal sizing for TES and SM values, set according to their most profitable values from Figures 6–8.

Table 6. Optimal TES and SM assessment for the three areas under study.

SM	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6
Vittoria optimal TES (eq. hours)	0	1	2	3	4	4	5	5	5
Posadas optimal TES (eq. hours)	0	1	2	3	4	5	6	6	6
Death Valley, CA optimal TES (eq. hours)	0	1	3	3	4	5	6	7	7

3.2. *Technoeconomic Sensitivity Analysis*

As shown in other works [14,15], economic analysis is focused on the LCOE. In (24), LCOE is used to compare the costs of electric-energy production according to the different plant configurations as a function of SM or TES:

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + O\&M_t + F_t)}{\sum_{t=1}^{n} E_t}, \tag{24}$$

The capital cost in year t is calculated in Equation (25):

$$I_t = crf \cdot I_c. \tag{25}$$

The capital recovery factor is calculated according to Equation (26):

$$crf = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} - k. \tag{26}$$

Considering a depreciation period of 25 years and a debt interest rate of 8.0%, the main data assumptions from Table 7 were used for the economic analysis [16].

Table 7. Main data for PT power plant—levelized cost of electricity (LCOE) calculation [16].

Concept	Units	Value
Site cost	€/m^2	13.33
Solar field investment	€/m^2	213.52
HTF system	€/kWh$_{th}$	210.95
Power-plant investment	€/kW$_e$	643.20
Two molten-salt-tank TES investment	€/KWh$_{th}$	52.74
Indirect investment cost and contingency surcharge	%	16.00
Fixed Operation and Maintenance (O and M) cost	€/kW$_e$/year	45
Variable O and M cost	€/MWh$_e$	3.50
Higher Heating Value (HHV) natural-gas fossil backup price	c€/kWh	2.87
Debt-interest rate	%	8.00
Annual insurance rate	%/year	0.50
Capital recovery factor	%	8.38
Plant lifetime	N	25

Regarding the considered radiation scenarios, electricity production and LCOE evolution values with SM were studied. Comparison results are represented in Figure 9 for Vittoria, Figure 10 for Posadas, and Figure 11 for Death Valley, CA. In this analysis, TES sizing for each SM value was according to Table 6.

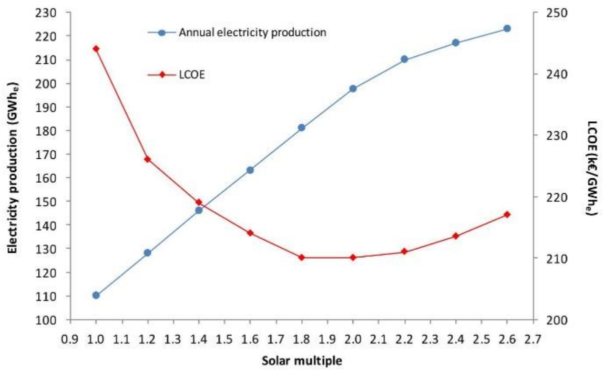


Figure 9. Annual net electricity generation and LCOE as SM function for Area 1, Vittoria.

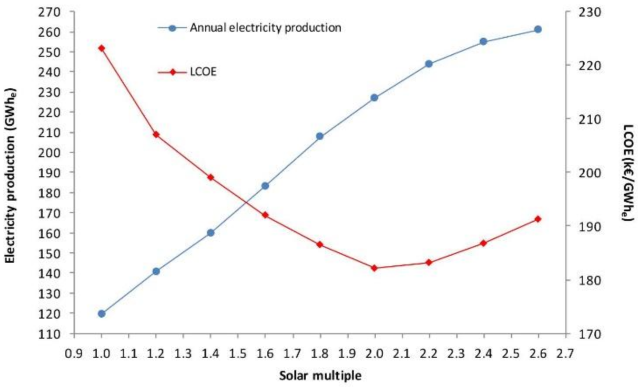


Figure 10. Annual net electricity generation and LCOE as SM function for Area 2, Posadas.

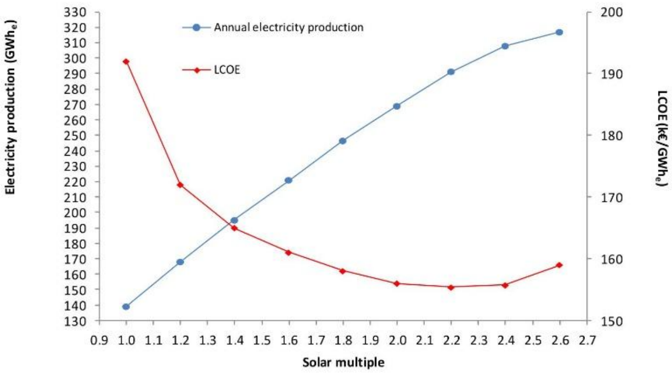


Figure 11. Annual net electricity generation and LCOE as SM function for Area 3, Death Valley, CA.

As shown in Figure 9, electricity production in Area 1 increased at the same time as SM and TES did, up to 223.08 GWh_e with SM = 2.6. However, the LCOE downtrend changed its tendency at SM = 1.8 and 209.92 k€/GWh_e as the critical point. With an optimal TES of 4, electricity generation over 181.64 GWh_e (SM = 1.8) was unable to balance the solar field, thermal-storage system, and Operation and Maintenance (O and M) investment. In Figure 10, an SM value of 2.0 was the most profitable solar-field size in order to obtain the maximum PT plant-investment optimization for Area 2. The best storage dimension of 5 equivalent hours for SM = 2.0 offered optimal electricity generation and LCOE values of 226.99 GWh_e and 182.08 k€/GWh_e, respectively. Regarding Figure 11, unless the electric generation uptrend rose to 317.60 GWh_e with SM = 2.6, values of SM above 2.2 carried an unprofitable tendency. At SM = 2.2, together with TES = 6, LCOE found its critical point. For this point, optimal plant sizing was set with a LCOE value of 155.35 k€/GWh_e and electricity production of 291.34 GWh_e.

3.3. Regulated- vs Deregulated-Electricity-Market Assesment

Optimal plant-design values were considered according to electrical production that minimizes LCOE, where generation best offsets plant investments. Economic results according to the most favorable LCOE values for each radiation scenario are represented in Table 8. REM and DEM gross average annual selling benefits were considered to set a comparison basic.

Table 8. Economic results for a 100 MW_e PT power plant with two-tank molten-salt TES.

Location	Vittoria	Posadas	Death Valley, CA
Solar-multiple value	1.8	2.0	2.2
Two-tank TES (equivalent hours)	4	5	6
Total investment cost per year (M€)	15.49	17.14	18.77
Annual O and M cost (M€)	5.51	5.77	6.10
Annual fuel-consumption cost (M€)	0.046	0.051	0.057
Annual net electric-energy production (GWh_e)	181.64	226.99	291.34
Capacity factor (%)	20.65	25.96	33.38
Annual LCOE (k€/GWh_e)	209.92	182.08	155.82
REM gross average annual benefit (M€)	11.89	14.53	19.04
DEM gross average annual benefit (M€)	15.20	18.58	24.30

As shown in Table 8, optimizing the LCOE does not imply plant-investment viability. For REM, in Areas 1 (Vittoria) and 2 (Posadas), the gross average annual benefit did not exceed the total investment cost per year. Only for Area 3 (Death Valley, CA) did it have an annual gross profit that overcame the total cost of investment at 1.42%. Regarding DEM, Area 2 and 3 benefits exceeded the investment costs by 7.75% and 22.76%, respectively. However, benefits in low-radiation scenarios like Area 1 do not match the cost of the plant, posing a viability disadvantage (–1.91%).

Second analysis involves a plant configuration that allowed the highest electricity-sales profit versus investment cost. Figures 12–14 show the total cost of investment per year and the average gross annual profit. Represented in Figures 12–14 is the REM and DEM evolution with MS for each of the three radiation scenarios. TES sizing for each SM value is according to Table 6.

According to Figures 12–14, plant sizing under REM found its optimal operation point at SM values of 1.8 for Vittoria, 2.0 for Posadas, and 2.2 for Death Valley. These values matched the results given in Table 8. For DEM, the most profitable plant operation in Area 1 (Vittoria) was made with SM = 2.0 and 4 TES equivalent hours, as shown in Figure 12. Nevertheless, gross average annual benefit (€16.70 M) did not rise above the annual investment cost (€16.89 M). Represented in Figure 13, an SM of 2.2 and TES of 6 was the best plant investment solution in Area 2 (Posadas). The benefits overcame plant investment costs by 8.07%. As plotted in Figure 14 for Area 3 (Death Valley), profit rose to €25.91 M with an SM of 2.4 and TES of 7. This is 22.77% over the annual investment cost of €20.01 M. Table 9 summarizes the optimal DEM investment results for the three areas under study.

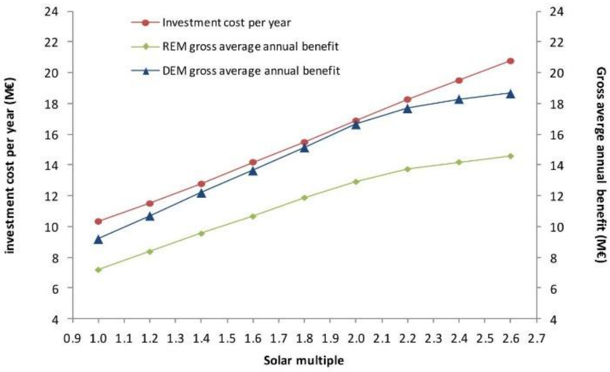


Figure 12. Investment cost per year and gross average annual benefit with SM for Area 1, Vittoria.

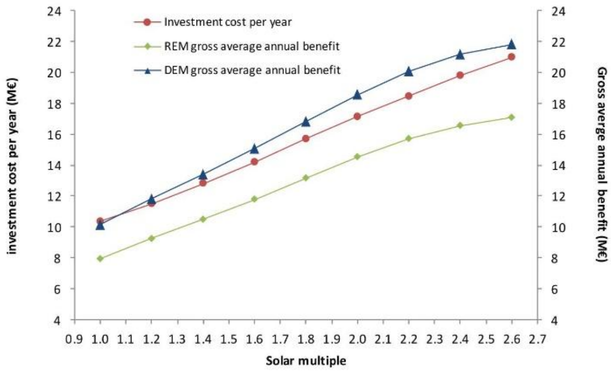


Figure 13. Investment cost per year and gross average annual benefit with SM for Area 2, Posadas.

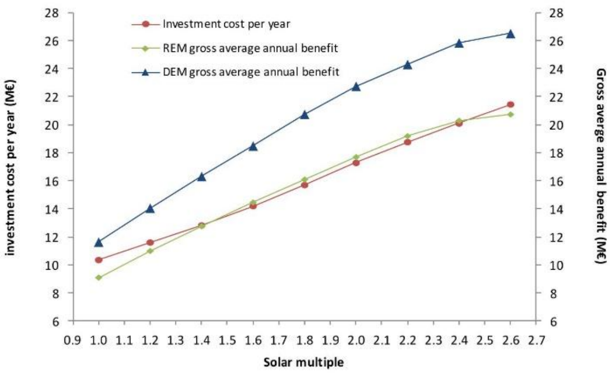


Figure 14. Investment cost per year and gross average annual benefit with SM for Area 3, Death Valley, CA.

Table 9. Optimal economic results in a DEM for a 100 MW_e PT power plant with two-tank molten-salt TES.

Location	Vittoria	Posadas	Death Valley, CA
Solar-multiple value	2.0	2.2	2.4
Two-tanks TES (equivalent hours)	4	6	7
Total investment cost per year (M€)	16.89	18.46	20.01
Annual O and M cost (M€)	5.66	5.93	6.25
Annual fuel-consumption cost (M€)	0.051	0.057	0.062
Annual net electric-energy production (GWh_e)	196.35	243.80	308.05
Capacity factor (%)	22.6	27.89	35.24
Annual LCOE (k€/GWh_e)	210.31	183.13	157.28
DEM gross average annual benefit (M€)	16.70	20.08	25.91

4. Discussion

The results obtained in this work for regulated markets, demonstrates that LCOE showed accurate analysis of the PT plant configuration. As shown in Figures 9–11, when the LCOE changed its downward trend, it decreased cost-production margins, making it unviable. Optimal plant sizing regarding SM, and therefore TES, for an optimal LCOE matches each radiation scenario with benefits against investment costs, as from Figures 12–14. In a deregulated market, electricity profit increment in high-priced periods makes optimal PT plant sizing tend to enhance SM and TES in any of the studied scenarios. Although LCOE moved from its best value, DEM improved average annual gross profit versus average annual total investment, as shown in Table 9.

Gross average annual benefit for electricity generation of deregulated against regulated markets was over 21% in all of the radiation areas under study. For medium- and high-radiation scenarios, DEM favors electricity sales profit to overcome investment costs for plant sustainability. Nevertheless, for low-radiation scenarios, benefits cannot offset investment costs, even in deregulated markets.

5. Conclusions

In this work, a 100 MW_e PT plant with a two-tank molten-salt TES was analyzed from an operation and market-behavior point of view. A mathematical simulation model was created and validated via a currently operated PT plant. Three locations representing different solar DNI scenarios were considered. Regulated and deregulated electricity-markets were considered for data analysis and investment optimization. Regarding solar resources and the electricity-markets, plant-sizing optimization was carried out according to [1.0:0.1:2.6] SM and [1:1:7] TES values.

Thus, the optimal dimensioning of a PT plant, considering as variables the size of the solar field and the thermal-storage capacity was shown in this paper, regarding the type of EM, for three different radiation scenarios. Based on this previous analysis, the electricity-production and LCOE evolution values with SM and TES were studied. In this technoeconomic analysis, the values of generated power that corresponded to an optimal value of LCOE, and therefore the optimal working points of the PT plant, were obtained. Finally, the optimal dimensioning values were parameterized in the operation of the PT plant under regulated and deregulated electricity-market requirements, obtaining the most profitable benefit results for each electricity-market scenario.

The main characteristic of the presented work was the great dimension-value vectors and the stochastic kind of values obtained depending on uncertain factors, such as weather forecast parameters. This study gives the best operation enouncement, and the obtained results allow for future- and historical-value analyses.

Author Contributions: J.M.L. and D.B. conceived and designed the mathematical model and its calibration, set up data acquisition from the currently operating PT power plant, and developed the study environment and the simulation model; M.R.d.A. helped with the simulation model and performed the calibration-model process; J.M.L. and D.B. analyzed the data; J.M.L. and D.B. wrote the paper.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge the collaboration in this work with the Engineering team of Africana Energía parabolic-trough solar-thermal power plant, located in Posadas (Spain).

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Parameters

a_i	Decision variables lower constraints
b_i	Decision variables upper constraints
A_E	Real collection surface for 100 MW_e solar thermal plant (m^2)
C_{Ct}	Thermal losses factor in solar field (%)
crf	Capital recovery factor (%)
E_{S_j}	Stored thermal energy in period j (MWh_{th})
E_S^{min}	Minimum stored thermal energy in period j (MWh_{th})
E_t	Annual insurance rate (%/year)
F_t	Fuel consumption cost in the year t (c€/kWh)
I_c	Plant investment cost per year (M€/year)
I_t	Capital cost in year t (€/kWh_e)
K	Annual insurance rate (%/year)
N_{AH}	Maximal stored energy in thermal tanks in annual period (equiv. hours of max. production (h))
P_{DE}	Nominal electricity power generated (MW_e)
P_{E_j}	Electricity power generated for period j (MW_e)
P_E^{min}	Minimum electricity power generated (MW_e)
Q_{DNI}	Maximum solar field direct normal irradiance received (MW_{th})
Q_{DNI_j}	Solar field direct normal irradiance received for period j (MWh_{th})
Q_{HCE-H_j}	Nominal thermal energy received from solar concentrators for period j (MWh_{th})
Q_{DTG}	Nominal thermal capacity to steam turbine (MW_{th})
Q_{TTI_j}	Thermal energy to steam turbine for period j (MWh_{th})
η_{HED-TS}	Storage-load efficiency (%)
η_{HED-FS}	Storage-unload efficiency (%)
η_{DTG}	Thermal–electrical conversion efficiency by design (%)
η_S	Solar thermal conversion efficiency as factor of optical efficiency and heat loses in pumps and pipes, accumulative efficiency coefficient (%)
$\Pi_{\_j}$	Generic price of electricity in the period j (€/MWh_e)
Π_{HMP_j}	High price of electricity (in deregulated market) in the period j (€/MWh_e)
Π_{LMP_j}	Low price of electricity (in deregulated market) in the period j (€/MWh_e)
Π_{RM_j}	Price of electricity in regulated market in the period j (€/MWh_e)
Π_{RM}^{max}	Maximum price of electricity in regulated market in the period j (€/MWh_e)

Variables

F_S	Solar multiple of solar-collection surface (%)
N_H	Maximal stored energy in thermal tanks (equiv. hours of max. production (h))
Q_{FS}	Thermal energy from the storage tanks to steam turbine (MWh_{th})
Q_{HCE-F}	Solar-field thermal energy received decrement due to collector fadeout (MWh_{th})
Q_{TS}	Thermal energy input to hot tank (MWh_{th})
R_{DNI}	Direct Normal Irradiance as solar resource (MWh_{th}/m^2)
x_i	Generic decision varibles
Π_{DM}	Price of electricity in deregulated market (€/MWh_e)

Index

DM	Daily market
DTG	Design parameters for steam turbine
HCE	Heat from solar field
HED-FS	Heat from thermal storage system
HED-TS	Heat to thermal storage system
i	Number of decision variables
j	Time as variable
J	Planning of operating period in hours
max	Maximal value
min	Minimal value

Acronyms

CS	Case Study
CSP	Concentrating Solar Power
CTS	Concentrating Thermosolar System
EM	Electricity Market
DEM	Deregulated Electricity Market
DIPS	Delayed Intermediate Production System
DNI	Direct Normal Irradiance
HHV	Higher Heating Value
HP	High Market Price
HSR	High solar Resource
HTF	Heat Transfer Fluid
LCOE	Levelized cost of electricity (k€/GWh$_e$)
LP	Low Market Price
LSR	Low Solar Resource
O and M	Operation and Maintenance
PLP	Peak Load Plant
PT	Parabolic Trough
REM	Regulated Electricity Market
SM	Solar Multiple
TGHP	Thermal Group Hourly Program

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DISCUSIÓN

La verdad se robustece con la investigación y la dilación; la falsedad, con el apresuramiento y la incertidumbre
CORNELIO TÁCITO (55 D. C. – 120 D. C.)

Para contrastar las hipótesis planteadas y alcanzar los objetivos establecidos en este trabajo, resulta fundamental la evaluación en términos cuantitativos de las propuestas de optimización de planta presentadas. Para ello, las variables utilizadas son el recurso solar, R_{DNI}, el SM del campo solar, F_S, el tamaño del sistema de almacenamiento, N_H, la energía térmica entregada a almacenamiento, Q_{TS}, la energía térmica de almacenamiento hacia el bloque de potencia, Q_{FS}, desenfoque de lazos en el campo de colectores, Q_{HCE-F}. Todo ello acorde a los diferentes escenarios de radiación estudiados, así como a las bandas de precios de electricidad dentro de los Mercados Eléctricos Regulado (REM) y no Regulado (DEM).

Entre las diferentes variables que intervienen en el modelo matemático planteado, se consideran como variables de decisión F_S y N_H, ya que su adecuada configuración permite establecer el tamaño óptimo de planta, cuya operación y mecanismos de venta, optimicen la producción y el beneficio económico, acorde a cada localización y mercado eléctrico en particular. La amplitud de los intervalos considerados en el **Artículo 6** para F_S y N_H, [1:0,1:2,6] y [0:1:7], permite analizar la influencia de su configuración en la producción eléctrica y los beneficios de la venta dentro de cada tipo de mercado, considerando los tres escenarios de radiación establecidos en dicho trabajo.

Así, el efecto del dimensionamiento del campo solar y del tamaño del sistema de almacenamiento térmico, sobre la potencia neta generada y los beneficios brutos de la venta de energía eléctrica, es evaluado cuantitativamente. Para ello, ha sido necesario el análisis de los costes de implantación, mantenimiento y operación acorde a la capacidad de generación, el estudio de los modos de operación dentro de los mercados eléctricos, así como la aplicación del factor de capacidad y el coste nivelado de la electricidad como indicadores de evaluación. Los resultados procedentes de los **Artículos 5 y 6** son usados para esta evaluación.

En las Figuras 4-9 se muestran los resultados para cada uno de los escenarios de radiación analizados en el **Artículo 6**, estos son: Vittoria, Italia (5 kWh_{th}/m^2), Posadas, España (6 kWh_{th}/m^2), y Death Valley, California (7 kWh_{th}/m^2). Así, las Figuras 4-6 muestran acorde a cada área de estudio, los resultados óptimos de dimensionamiento y operación obtenidos por tipo de mercado eléctrico, REM y DEM, considerando LCOE y el gradiente "Beneficio de la venta de electricidad frente a Coste de Inversión" como parámetros de evaluación tecno-económica.

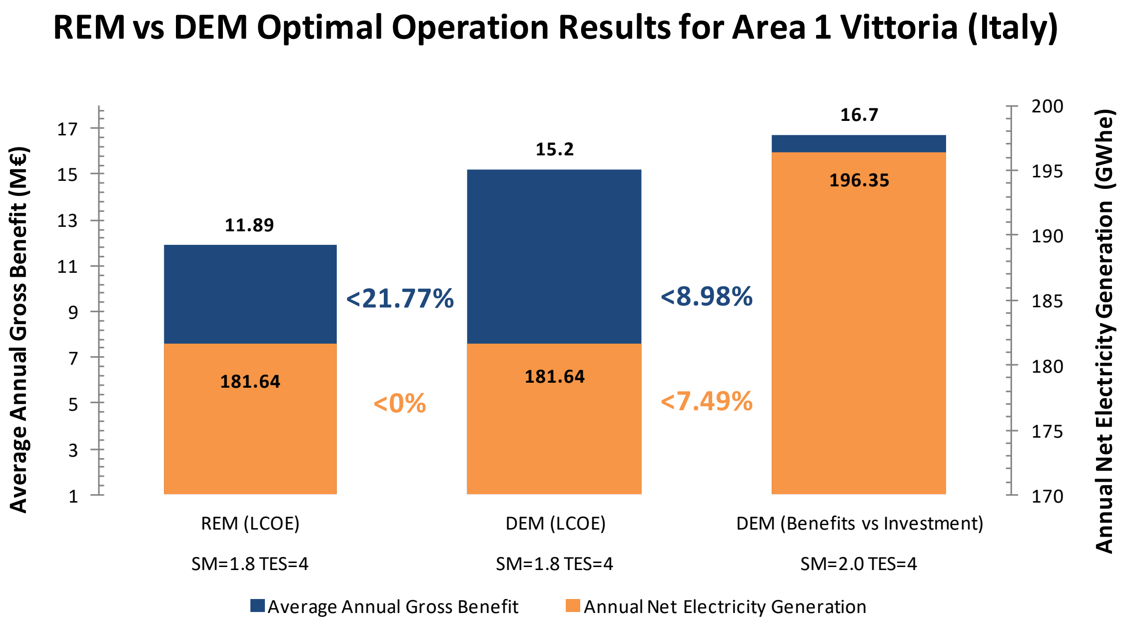


Figura 4. Resultados óptimos de dimensionamiento y operación según REM y DEM, en función del parámetro de evaluación, para el escenario de radiación 1 (Vittoria, Italia). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market*.

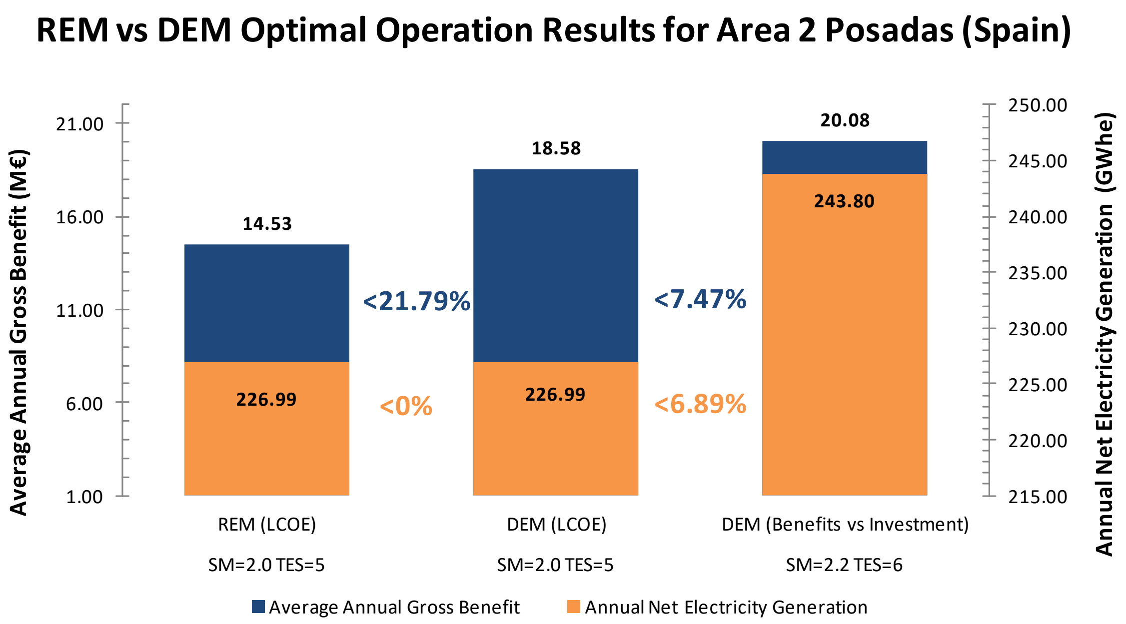


Figura 5. Resultados óptimos de dimensionamiento y operación según REM y DEM, en función del parámetro de evaluación, para el escenario de radiación 2 (Posadas, España). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market*.

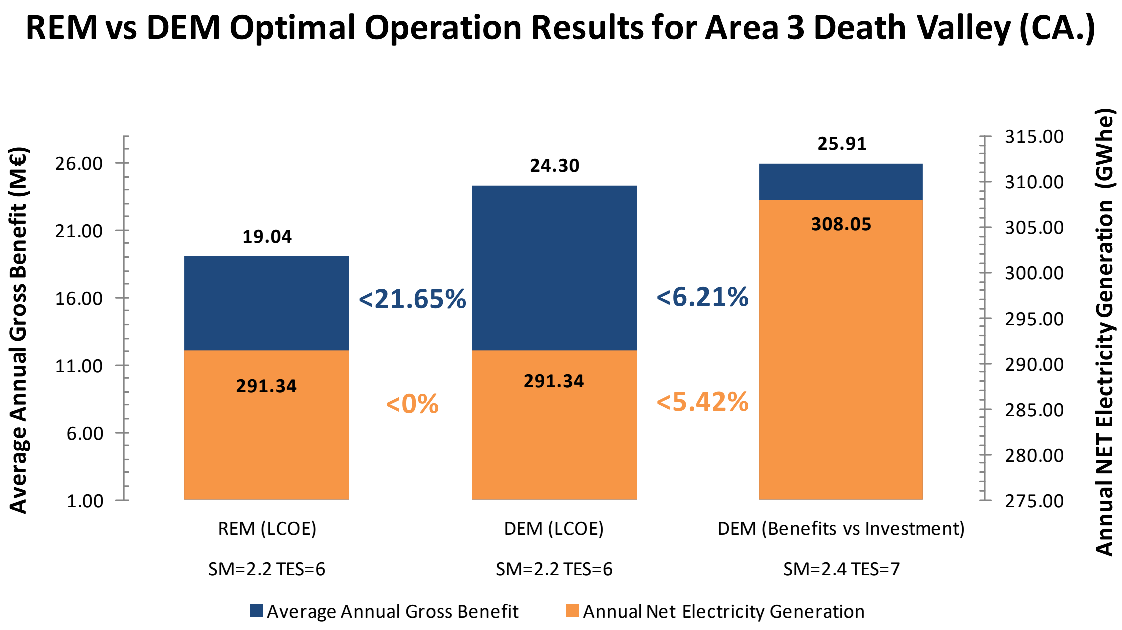
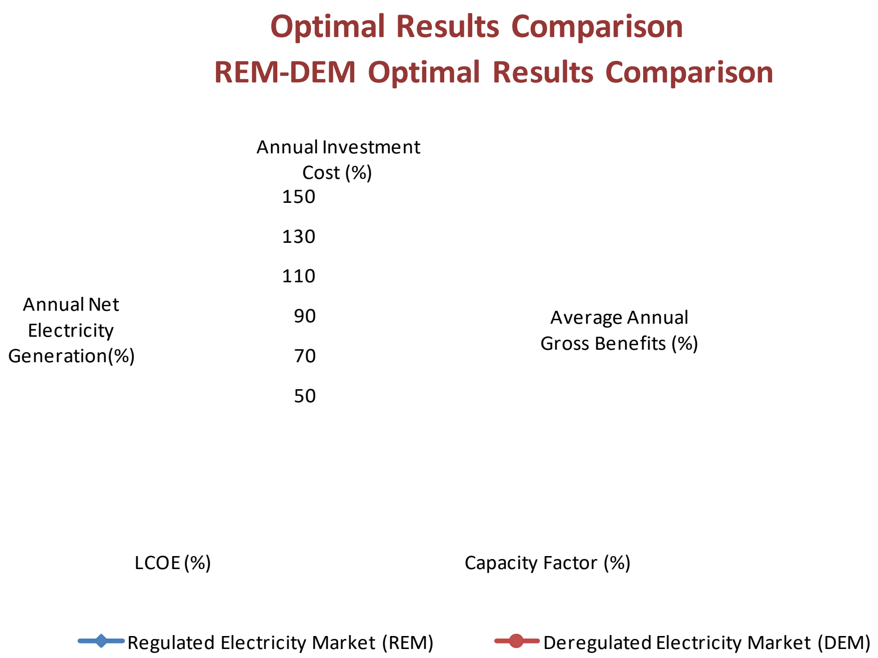


Figura 6. Resultados óptimos de dimensionamiento y operación según REM y DEM, en función del parámetro de evaluación, para el escenario de radiación 3 (Death Valley, California). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market*.

En las Figuras 4-6, un primer bloque de resultados muestra el aumento de beneficios de DEM sobre REM, para un mismo instrumento de evaluación (LCOE). Bajo este patrón de análisis, la configuración de planta así como la generación de electricidad no varían, siendo modificado únicamente el tipo de mercado eléctrico en el que se opera. El aumento del beneficio bruto dado es del 21,77% para Vittoria, 21,79% para Posadas y 21,65% para Death Valley. Por su parte, considerando únicamente DEM, el incremento del beneficio de la relación “Beneficios – Coste de Inversión” sobre LCOE muestra un aumento del 8,98, 7,47 y 6,21% para Vittoria, Posadas y Death Valley respectivamente. Los resultados mostrados presentan dos aspectos importantes a analizar. Por un lado, se obtiene un elevado beneficio porcentual obtenido por el cambio del tipo de mercado dentro del indicador LCOE, frente al obtenido por la mayoración de la planta de generación (Beneficios – Coste de Inversión). Por otro lado y considerando DEM, tanto la energía eléctrica generada como los beneficios brutos aumentan con tendencia similar para los tres escenarios estudiados, pero con valores porcentuales decrecientes según se dispone de mayor recurso solar.

Por su parte, en las Figuras 7-9, se muestra una comparativa entre los principales indicadores de optimización de planta CCP para cada área de radiación analizada, acorde a los mejores resultados de operación y venta de electricidad del **Artículo 6**, procedentes de "*Table 8*" para REM, con LCOE como herramienta de evaluación, y "*Table 9*" para DEM, tomando como herramienta el gradiente "Beneficios–Coste de Inversión". En las Figuras 7-9, la comparativa de resultados se presenta tomando el REM en función de DEM.

REM vs REM main Optimizing Indicators Comparison for Area 1 (Vittoria, Italy)



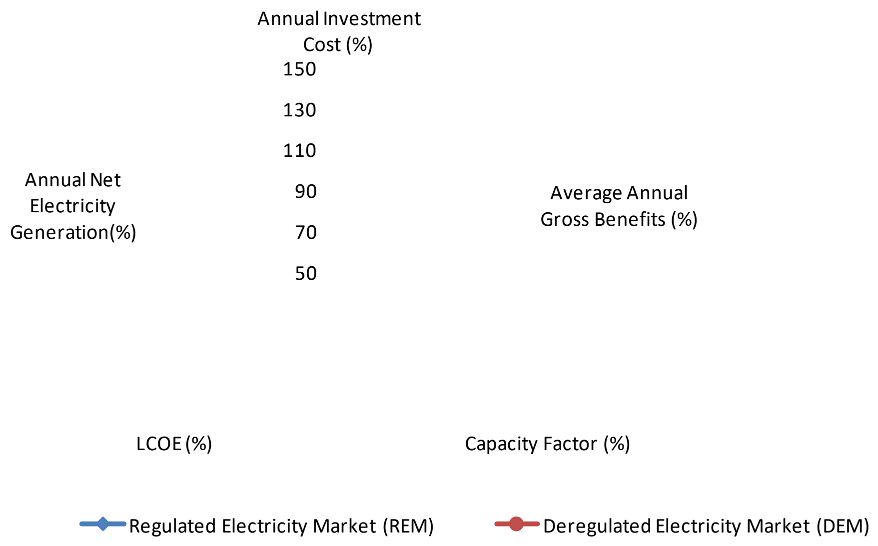
Deviation Values assessment

Indicator	REM Value	DEM Value	Deviation (%)	Deviation assessment
LCOE (k€/GWhe)	209.92	210.31	0.18	Loss
Annual Net Electricity Generation (GWe)	181.64	196.35	7.49	Gain
Annual Investment Cost (M€)	15.49	16.89	8.29	Loss
Average Annual Gross Benefits (M€)	11.89	16.70	28.80	Gain
Capacity Factor (%)	20.60	22.60	8.85	Gain

Figura 7. Comparativa entre los principales indicadores de optimización, tomando REM en función de DEM, para el escenario de radiación 1 (Vittoria, Italia). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market*.

REM vs DEM main Optimizing Indicators Comparison for Area 2 (Posadas, Spain)

REM-DEM Optimal Results Comparison



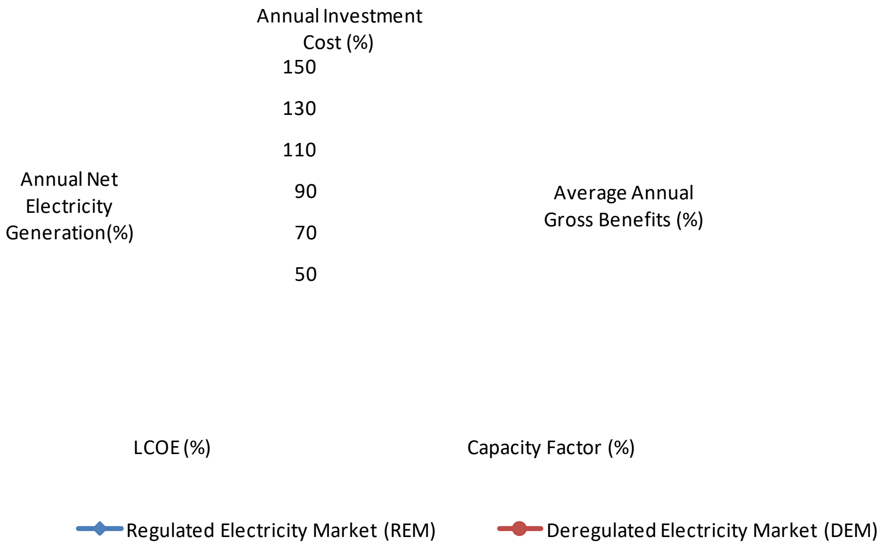
Deviation Values assessment

Indicator	REM Value	DEM Value	Deviation (%)	Deviation assessment
LCOE (k€/GWhe)	182.08	183.13	0.57	Loss
Annual Net Electricity Generation (GWe)	226.29	243.80	7.18	Gain
Annual Investment Cost (M€)	17.14	18.46	7.15	Loss
Average Annual Gross Benefits (M€)	14.53	20.08	27.64	Gain
Capacity Factor (%)	25.96	27.89	6.92	Gain

Figura 8. Comparativa entre los principales indicadores de optimización, tomando REM en función de DEM, para el escenario de radiación 2 (Posadas, España). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market.*

REM vs DEM main Optimizing Indicators Comparison for Area 3 (Death Valley, CA.)

Optimal Results Comparison
REM-DEM Optimal Results Comparison



Deviation Values assessment

Indicator	REM Value	DEM Value	Deviation (%)	Deviation assessment
LCOE (k€/GWhe)	155.82	157.28	0.93	Loss
Annual Net Electricity Generation (GWe)	291.34	308.05	5.42	Gain
Annual Investment Cost (M€)	18.77	20.01	6.20	Loss
Average Annual Gross Benefits (M€)	19.04	25.91	26.51	Gain
Capacity Factor (%)	33.38	35.24	5.28	Gain

Figura 9. Comparativa entre los principales indicadores de optimización, tomando REM en función de DEM, para el escenario de radiación 3 (Death Valley, California). DEM, *Deregulated Electricity Market*; REM, *Regulated Electricity Market*.

Para cada uno de los tres escenarios estudiados, en las Figuras 7-9 se representa la variación de los resultados óptimos de dimensionamiento y operación de planta, considerando REM respecto a DEM. Se toman el LCOE y el "Beneficio-Coste de Inversión" como instrumentos de evaluación para REM y DEM respectivamente. Los principales indicadores de optimización para cada área de radiación estudiada son analizados. Así mismo, se especifica si esta variación representa una mejora *"Gain"* o un empeoramiento *"Loss"*, provocado por el cambio de Mercado Eléctrico, de Regulado a No Regulado.

Como se muestra en la figura 7 para la zona de estudio 1 (Vittoria), los costes promedio de inversión anual en relación a la capacidad de generación de electricidad para el mismo periodo, arrojan unos valores de LCOE y de factor de capacidad que no posibilitan la obtención de beneficios por la venta de electricidad dentro de mercados regulados. Siendo por tanto los beneficios medios anuales un 23,24% inferior a los costes de inversión para este tipo de mercado en zonas de baja radiación normal directa. Dentro de mercados no regulados, la posibilidad de operar permite aumentar los beneficios medios anuales, no obstante este factor no es suficiente quedando un 1,12% por debajo de los costes de inversión. Así mismo para la zona de estudio 2 (Posadas), la relación entre el beneficio bruto medio anual y el coste promedio anual de inversión del -15,23%, y +8,77% para de REM y DEM respectivamente, posibilitando esta localización la obtención de beneficios dentro de mercados no regulados. Por su parte para la zona 3 (Death Valley), esta relación para REM y DEM es del +1,42% y +22,77%, donde tanto para REM como DEM El análisis tecno-económico muestra viabilidad para la implantación de plantas CCP en zonas de alta radiación normal directa. Los resultados presentados muestran la importancia de la localización como factor de decisión en la implantación de plantas CCP.

Considerando la comparativa REM-DEM, el indicador con mayor incremento es el beneficio medio bruto anual *"Average Anual Gross Benefit"*, para todos los escenarios de radiación. La ganancia aportada por este indicador de DEM respecto a REM es 28,8% para Vittoria, 27,64% para Posadas y del 26,51% para Death Valley.

Los indicadores que muestran un empeoramiento en sus resultados, es decir, que su incremento favorecen la configuración de planta a través de la evaluación del LCOE, en detrimento de "Beneficio-Coste de inversión", son el propio LCOE y el coste promedio anual de la inversión *"Annual Investment Cost"*. No obstante, la desviación del dimensionamiento óptimo mostrado no es suficiente para contrarrestar la ganancia en el resto de indicadores, y principalmente el beneficio por el beneficio medio bruto anual *"Average Anual Gross Benefit"*.

LIMITACIONES DEL TRABAJO

Somos lo que hacemos de forma repetida. La excelencia, entonces, no es un acto, sino un hábito
WILLIAM JAMES DURANT
LA HISTORIA DE LA FILOSOFÍA. CAPÍTULO II, VII

La investigación realizada en este trabajo se ha llevado a cabo a partir de una planta de generación eléctrica CCP con potencia neta máxima de 50 MW_e situada en la provincia de Córdoba (España). Esta capacidad de generación corresponde con el tamaño mayor de planta, dentro de la actividad en régimen especial, que permite la legislación actual en el sector eléctrico español para *"centrales utilicen como energía primaria energías renovables o residuos, y aquellas otras como la cogeneración que implican una tecnología con un nivel de eficiencia y ahorro energético considerable"* [*LEY 54/1997*][*LEY 17/2007*].

Dada la disponibilidad geográfica y de acceso, la mencionada planta de generación se ha tomando como base para el desarrollo del modelo de optimización, así como para la validación del mismo. De forma general, este hecho limita el alcance de las conclusiones de esta Tesis, dado que el modelo desarrollado no ha sido ensayado ni validado con centrales de mayor capacidad de generación. Así, factores derivados de la mayoración de los diferentes sistemas que componen la planta CCP pueden requerir modificaciones en el modelo planteado.

Por su parte, las principales limitaciones específicas de este trabajo se enumeran a continuación:

- Referente a la incidencia del recurso solar sobre el campo de colectores, en este trabajo se han considerado niveles de Radiación Normal Directa *"Direct Normal Irradiance"* (DNI) correspondientes a cada localización geográfica estudiada. Del mismo modo, para el proceso de modelado, han sido considerados tanto valores de DNI como de coberturas parciales procedentes de nubes. No obstante, el comportamiento del modelo frente a coberturas parciales debidas, entre otros, a procesos niebla o arena en suspensión no ha podido ser contrastado, afectando por tanto, a la viabilidad del modelo en localizaciones geográficas donde estos procesos son comunes.

- La dificultad de acceso a la parametrización y análisis del bloque de potencia en las plantas CCP estudiadas, principalmente turbina de vapor, limita la adopción de trabajos de optimización que ayuden a mejorar la eficiencia en este sistema, y por tanto, mayorar la producción de electricidad.

- En relación a los precios de electricidad, la adaptación de este modelo de operación al mercado eléctrico de otros países o regiones, requiere la importación de los datos correspondientes a los históricos de precios de venta para cada tipo y configuración de mercado.

CONCLUSIONES Y PROSPECTIVA

La verdadera causa final reside en los seres inmóviles
ARISTÓTELES, METAFÍSICA, LIBRO XII, VII

A continuación, se muestran las principales conclusiones obtenidas en este trabajo de Tesis Doctoral, procedentes del estudio de las plantas termosolares de generación eléctrica, con sistema de campo de colectores cilindro parabólicos, dentro de la tecnología de receptor central. La revisión bibliográfica llevada a cabo, el estudio de campo y la validación del modelo matemático implementado, han permitido detectar las necesidades reales de funcionamiento de planta, así como aspectos tecno-económicos y de mercado eléctrico aún no abordados en la literatura existente. Así mismo, se exponen las posibles líneas futuras de investigación, establecidas a partir de los resultados obtenidos, y encaminadas a la optimización del diseño, implementación y operación de plantas de generación eléctrica CCP.

CONCLUSIONES

Las conclusiones y consideraciones principales que se derivan del presente trabajo de Tesis Doctoral son las siguientes:

1. Un sistema de almacenamiento térmico inédito e innovador denominado "HTF Buffering" se ha presentado en esta Tesis Doctoral. El sistema se forma a través de la generación de un bucle de fluido térmico dentro del campo solar. El análisis presentado, con un coste nivelado de energía eléctrica de 144,05 k€/GWh_e, y un factor de

capacidad de 33,77%, lo convierte en una alternativa viable a los sistemas tradicionales de almacenamiento tanto a nivel técnico como económico. De igual modo y tras la publicación del artículo 4 de esta Tesis Doctoral, la implementación del sistema propuesto se ha realizado en centrales que se encuentran actualmente en operación.

2. La optimización combinada del dimensionamiento-operación de planta y operación mercado realizada consiste en la optimización capacidad de generación, así como el ajuste de la producción de electricidad a la curva de demanda y precios variables del mercado eléctrico bajo las mejores condiciones económicas, para cada una de las situaciones de producción estudiadas. Esta optimización procedente del análisis de cuatro casos de estudio dados por las combinaciones de la disponibilidad de recurso solar y del precio de la electricidad para una planta de 50 MW_e con almacenamiento de energía térmica dentro de un mercado eléctrico no regulado, arroja para el ciclo completo de un año tipo un incremento de la generación neta de energía eléctrica y de los beneficios de venta brutos obtenidos, mayores de 5,45% y 5,17% respectivamente, respecto a la generación estándar por análisis algebraico directo.

3. El trabajo presentado, combinando dimensionamiento-operación de la planta solar y operación de mercado eléctrico para una central de 100 MW_e con almacenamiento térmico mediante doble tanque de sales fundidas, consiste en el desarrollo de estrategias de operación que optimicen la producción de electricidad y reduzcan los costes de implantación a través del dimensionado óptimo del campo solar y del sistema de almacenamiento de energía térmica. Estas estrategias se han basado en el pronóstico y ajuste de la curva de generación de electricidad a la demanda del mercado eléctrico para mercados

regulados, y en el pronóstico y ajuste de la curva de generación a la demanda y precios del mercado eléctrico para mercados no regulados. Así, los resultados de este estudio muestran la configuración del campo solar y del sistema de almacenamiento de energía térmica que optimiza el funcionamiento y operación de la planta para cada uno de los escenarios estudiados. Esta optimización se ha llevado a cabo para mercados eléctricos regulado y no regulado, donde se han comparado resultados en tres localizaciones diferentes atendiendo a baja, media y alta radiación normal directa. Los resultados obtenidos para mercados eléctricos regulados muestran el valor del coste nivelado de la energía que proporciona la configuración que maximiza la eficiencia de tecno-económica de la planta, estos son 209,92 k€/GWh$_e$, 182,08 k€/GWh$_e$ y 155,82 k€/GWh$_e$ respectivamente para zonas de baja, media y alta radiación normal directa. Siendo los respectivos valores de configuración óptima de campo solar y tamaño de sistema de almacenamiento térmico 1,8 y 4,0 para zonas de baja, 2,0 y 5,0 para zonas de media y 2.2 y 6,0 en zonas de alta radiación normal directa. Para mercados eléctricos no regulados, el análisis económico realizado en este estudio proporciona datos relevantes sobre la sostenibilidad de implantación de planta para cada uno de los escenarios estudiados, con una relación beneficio de producción frente a costes de implantación de 98,87%, 108,77% y 129,48%, para zonas de baja, media y alta radiación normal directa respectivamente. De igual modo, los valores de configuración de campo solar y tamaño de sistema de almacenamiento térmico óptimos que proporcionan estos valores son 2,0 y 4,0 para zonas de baja, 2,2 y 6,0 para zonas de media y 2.4 y 7,0 en zonas de alta radiación normal directa.

Los resultados obtenidos son aplicables a cualquier planta, con independencia de su capacidad de generación eléctrica. Estos resultados posibilitan la reducción de los costes directos, concretamente los relativos al cambio de diseño en el proceso de implantación, mediante el ajuste preciso de su dimensionado así como el estudio previo de los sistemas que mejor se ajusten a cada planta en particular y tipo de mercado eléctrico, como el sistema de almacenamiento de energía o el campo solar. Así mismo, permiten establecer un análisis preciso del modo de operación de planta, optimizándolo acorde al estado de las variables clave como disponibilidad de recurso solar, coberturas parciales o totales, capacidad de generación térmica, capacidad de almacenamiento de energía, demanda de energía eléctrica de la red y capacidad de producción de energía eléctrica.

PROSPECTIVA

La presente investigación junto con las características del modelo desarrollado, sientan las bases para futuros estudios donde poder extrapolar e implementar los resultados aquí obtenidos. Entre otros, la comparativa entre los sistemas de almacenamiento térmico *"HTF Buffering"* y doble tanque de sales fundidas, o la influencia del tamaño de la planta CCP en el comportamiento tecno-económico y de operación de la planta.

Así mismo, como futura línea de investigación resulta de especial interés el modelado y estudio de plantas con colectores cilindro parabólicos que contienen sales fundidas como fluido caloportador en el campo solar. Se trata de un desarrollo sobre el modelo tradicional actualmente en auge para plantas de mayor potencia. La elevada temperatura de tránsito soportada por las sales permite reducir los costes de implantación para una misma capacidad de producción. No obstante, la escasa experiencia en campo y los problemas derivados del envejecimiento prematuro de los materiales y componentes hacen de este sistema un objeto prioritario de estudio.

De igual modo, el análisis del dimensionado del bloque de potencia, y las características de la turbina de vapor se presenta como factor objetivo de futuros estudios. Principalmente debido a la adopción en las centrales termosolares de las configuraciones propias de centrales eléctricas clásicas donde el trabajo termodinámico realizado, así como la entrega de energía al bloque de potencia difieren mucho a las particularidades de este tipo de plantas. Factores de estudio principales a destacar son la continuidad en la generación y entrega de energía al bloque de potencia, diferentes periodos de parada y arranque o equilibrio entre el tamaño de la turbina y la capacidad térmica generada.

Por último, futuros trabajos han de contemplar, no sólo los costes de operación y mantenimiento como han sido tenidos en cuenta en este estudio, sino también los derivados de la obsolescencia programada de los elementos que componen la central de generación. El análisis del tipo y velocidad de envejecimiento de estos elementos ofrece información relevante que afecta a la lista de repuestos recomendada, ajuste del mantenimiento predictivo, previsión de horas de funcionamiento anual y análisis del estado de conservación de la planta, entre otros.

FINAL CONCLUSIONS AND FUTURE LINES

A final cause can be found in a way in the realm
of immovable things
ARISTOTLE, METAPHYSICS, BOOK XII, VII

Regarding the study of parabolic trough solar thermal power plants addressed within central receiver technology, the following are the main conclusions obtained from this doctoral dissertation. The bibliographic review carried out, the field survey as well as the validation of the mathematical model implemented made possible to detect the plant managing needs, together with techno-economic and market aspects not covered in previous work. Similarly, the future research lines are focused enabled from the results obtained, and aimed at optimising the design, investment and operation of PT solar thermal power plants.

FINAL CONCLUSIONS

The main conclusions derived from the present work of Doctoral Thesis are as follows:

1. An innovative and unpublished thermal storage system called "HTF Buffering" has been introduced in this Doctoral Thesis. This system is formed through the generation of a thermal fluid buffer within the solar field. The presented analysis, with a levelized cost of electricity of 144.05 k€/GWh$_e$, and capacity factor of 33.77%, makes "HTF Buffering" a viable alternative to traditional storage systems both technically and economically. In addition, following the publication of article 4 of this

Doctoral Thesis the proposed system has already been implemented in currently operated PT plants.

2. The combined optimization of the plant sizing-operation and market operation carried out consists in the optimization of generating capacity, as well as the adjustment of electricity production to the demand curve and variable prices of the electricity market under the best economic conditions for each of the production situations studied. This optimization carried out from the analysis of four case studies given by the combinations of solar resource availability and electricity price, of a 50 MW_e plant with thermal energy storage within a deregulated electricity market, yield for the full cycle of a year an increase in net electricity generation and gross sales profits obtained, greater than 5.45% and 5.17% respectively, compared to standard generation by direct algebraic analysis.

3. The work herein presented, combining plant sizing-operation and electricity market operation of a 100 MW_e plant with thermal storage by double molten salt tank, consist in the development of strategies that optimize the electricity generation as well as reduce the investment cost throughout the optimization of the solar field and the thermal energy storage system. In regulated electricity markets, these strategies consist of forecasting and adjusting the electricity generation curve to the demand of the market. For deregulated markets, the forecasting and adjustment of the generation curve to the demand and prices of the electricity market. Thus, results in this work show the configuration of the solar field and thermal energy storage system that optimizes the managing and operation of the plant. This optimization has been carried out for regulated and deregulated electrical markets, where results have

been compared in three different locations according to low, medium and high direct normal irradiance. The results obtained for regulated electrical markets show the value of the levelized cost of electricity that maximizes the techno-economic efficiency of the plant, being 209.92 k/GWh$_e$, 182.08 k/GWh$_e$ and 155.82 k/GWh$_e$ respectively for low, medium and high direct normal radiation zones. The respective values of optimal solar field and thermal storage system size are 1.8 and 4.0 for low, 2.0 and 5.0 for medium, and 2.2 and 6.0 for high areas of direct normal irradiance. Regarding deregulated electricity markets, the study provides relevant data about the economic sustainability of its implementation for each of the scenarios analyzed. Values of production benefit ratio versus implementation costs are 98.87%, 108.77% and 129.48%, for low, medium and high direct normal irradiance areas respectively. Similarly, the optimal solar field and thermal storage system size settings provided by these values are 2.0 and 4.0 for low, 2.2 and 6.0 for medium, and 2.4 and 7.0 for high areas of high direct normal irradiance.

The results obtained are applicable regardless of the power generation capacity of the plant. They enable direct Cost saving in the implementation process, through the plant sizing optimization and the analysis of the systems that best fit each particular power plant and electricity market type, such as the energy storage system or the solar field.

Results also allow an accurate analysis of the plant operation mode. This operation mode is optimised according to key factors such as solar resource availability, partial or total solar coverage, thermal generation capacity, thermal energy storage, grid's electricity demand, and electricity generation capacity.

FUTURE LINES

This research, together with the features of the developed model, lay the foundation for future studies where the results obtained could be extrapolated and implemented. Among others, the comparison between "HTF Buffering" and double tank of molten salts thermal storage systems, or the influence of the PT plant size on the technoeconomic and operating behaviour of the whole system.

Likewise, it is of particular concern the modelling and study of parabolic trough plants with molten salt as heat transfer fluid in the solar field as a future research line. This development of the traditional model is currently as it peak for large parabolic trough plant. The high transfer temperature supported by molten salt reduces the implementation costs for the same plant production capacity. However, limited field experience and problems arising from premature ageing of materials and components make this system a priority goal of study.

In addition, the sizing analysis of the power block and steam turbine characteristics are objective factors for future assessments. It is mainly due to the adoption of classic power plants configurations into thermo-solar systems. The thermodynamic work carried out along with the energy delivery into the power block varies widely in each system. The main factors of study to be highlighted are the study of the power generation and power block delivery, downtimes and turbine size vs. thermal capacity generated balance.

Finally, future analysis work must consider not only the costs of operation and maintenance but also the costs derived from of the planned obsolescence of the power plant systems. The analysis of the type and speed of systems again provides relevant information that affects mainly the recommended spare parts list, predictive maintenance adjustment, annual operating hours forecast and general status of the power plant.

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Clave	**Artículo 4**
Título	Techno-economic assessment of heat transfer fluid buffering for thermal energy storage in the solar field of parabolic trough solar thermal power plants.
Autores	Jorge M. llamas, David Bullejos, Manuel Ruiz de Adana
Nombre de la revista	Energies
Año, Volumen, páginas	2017, 10, 1123
Editorial	MDPI AG
Revista incluida en Journal Citation Reports (JCR)	Sí
Índice de impacto (2017)	2.676
Categoría	Energy and Fuels
Lugar que ocupa la revista en la categoría	48/97
Cuartil	Q2

Clave	**Artículo 5**
Título	Optimal operation strategies into deregulated markets for 50 MW_e parabolic trough solar thermal power plants with thermal storage.
Autores	Jorge M. llamas, David Bullejos, Manuel Ruiz de Adana
Nombre de la revista	Energies
Año, Volumen, páginas	2019, 12, 935
Editorial	MDPI AG
Revista incluida en Journal Citation Reports (JCR)	Sí
Índice de impacto (2017)	2.676
Categoría	Energy and Fuels
Lugar que ocupa la revista en la categoría	48/97
Cuartil	Q2

Clave	**Artículo 6**
Título	Optimization of 100 MW_e parabolic trough solar thermal power plants under regulated and deregulated electricity markets.
Autores	Jorge M. llamas, David Bullejos, Manuel Ruiz de Adana
Nombre de la revista	Energies
Año, Volumen, páginas	2019, 12, 3973
Editorial	MDPI AG
Revista incluida en Journal Citation Reports (JCR)	Sí
Índice de impacto (2017)	2.676
Categoría	Energy and Fuels
Lugar que ocupa la revista en la categoría	48/97
Cuartil	Q2

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